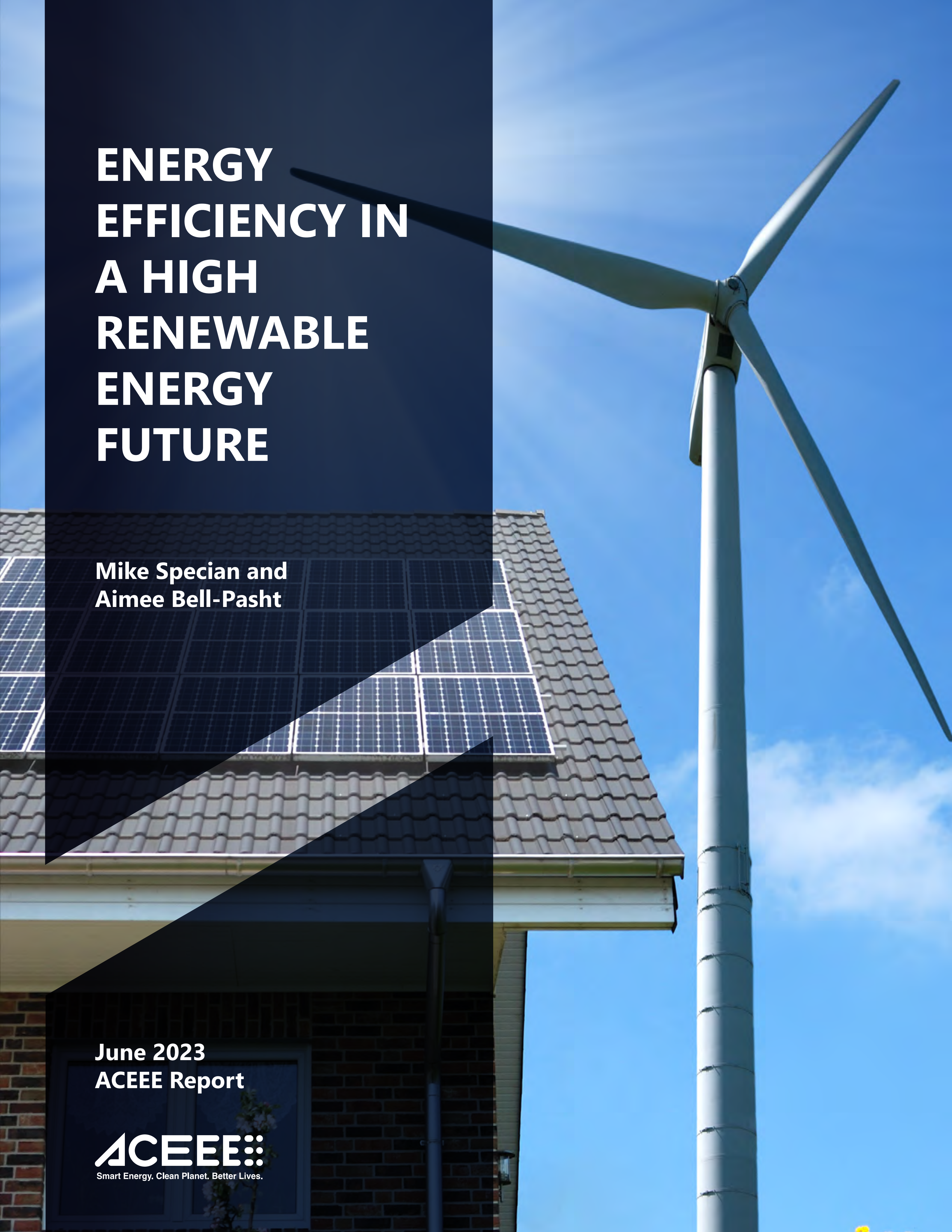

ENERGY EFFICIENCY IN A HIGH RENEWABLE ENERGY FUTURE

Mike Specian and
Aimee Bell-Pasht

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ACEEE Report

ACEEE
Smart Energy. Clean Planet. Better Lives.

Contents

About ACEEE

The **American Council for an Energy-Efficient Economy** (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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Executive Summary

KEY FINDINGS

- Our analysis shows that energy efficiency has a crucial role in decarbonizing the electricity system and paving the way for a high renewable energy future. This result holds even if low levels of building electrification depress future electricity demand.
- Energy efficiency provides more value the more quickly electricity generation decarbonizes by offsetting the escalating costs of fossil-based energy and carbon capture under high renewable energy scenarios.
- We analyzed 5 of the 20 grid regions covering the continental United States (i.e., California, Texas, the Pacific Northwest, the Southeast, and the Midwest). We found that energy efficiency reduces costs that would otherwise be passed on to customers by avoiding energy, generation capacity, and transmission costs, with estimated savings of $10–19 billion annually per grid region analyzed by 2050.
- Energy efficiency can reduce the maximum annual load that must be met with nonrenewable sources (i.e., net peak load) 31–46% in 2030 and 39–86% in 2050 even in the absence of widespread electrification.
- Energy efficiency measures that affect thermal space conditioning loads (i.e., heating and cooling) are likely to have the greatest impact on both energy savings and avoided electricity system costs through 2050. Delivering these benefits to low-income customers may require overcoming additional impediments like mold and structural damage to their homes.
- After thermal space conditioning measures, the energy efficiency measure with the highest potential to reduce electric system costs through mid-century is the installation of residential heat pump water heaters.
- The electricity system benefits provided by energy efficiency grow through mid-century as old equipment wears out and more efficient equipment is installed.

The United States has committed to reducing its greenhouse gas emissions 50–52% below 2005 levels by 2030. As part of this commitment, the United States has set a goal of reaching 100% carbon-free electricity by 2035. In this report, we examine the role that a demand-side intervention—energy efficiency—will play in helping enable this decarbonized high renewable energy future.

METHODOLOGY

This report is the result of a literature review; quantitative modeling of the benefits of energy efficiency on the future, high renewable energy electric grid; and expert consultation. We consider energy efficiency's role in a high renewable energy future in two parts. First, we consider energy efficiency in the aggregate by conducting a literature review of prominent reports that lay out feasible pathways to achieve either a high renewable energy or deep decarbonization future, and closely examine the role energy efficiency plays within them.

Second, we model and analyze energy efficiency at a granular level, exploring which specific residential and commercial energy efficiency measures or packages are most effective at avoiding different electricity system costs in 2030 and 2050 (see table ES-1). To understand how these results vary across the United States, we focus our analysis on five regions: California, Texas, the Southeast, the Midwest, and the Northwest. To understand how the rate of renewable energy deployment affects our results, we study two renewable energy scenarios—one in which the U.S. electricity sector mostly decarbonizes by 2050, and another in which it mostly decarbonizes by 2035.

Table ES-1. List of residential and commercial energy efficiency measures modeled in our analysis. SEER=seasonal energy efficiency ratio; CEF=combined energy factor; EF=energy factor; LED=light-emitting diode; IMEF=integrated modified energy factor; HVAC=heating, ventilation, and air conditioning.

Measure	Sector	Definition
Thermal space conditioning–central air conditioner	Residential	Envelope improvements (i.e., wall insulation, foundation insulation, windows), Internet-connected thermostat, plus SEER 18 central air conditioner
Thermal space conditioning–air source heat pump	Residential	Envelope improvements, Internet-connected thermostat, plus SEER 22 air source heat pump
Thermal space conditioning–smart thermostat only	Residential	Envelope improvements plus Internet-connected smart thermostat
Heat pump water heater (HPWH)	Residential	80-gallon electric heat pump water heater with 2.4 coefficient of performance
Clothes dryer	Residential	Ventless heat pump dryer with CEF = 3.65
Electronics	Residential	Plug loads usage level halved
Refrigeration	Residential	EF 22.2 refrigerator
Lighting	Residential	LEDs, 112 lumens/Watt
Pool pump	Residential	0.75 horsepower pump with 1,688 kWh annual energy use
Clothes washer	Residential	ENERGY STAR Most Efficient (IMEF ≥2.92)
Dishwasher	Residential	Rated 199 kWh/year

Measure	Sector	Definition
Refrigeration	Commercial	Various minimum performance levels for reach-in freezers, walk-in freezers, reach-on refrigerators, walk-in refrigerators, and supermarket display cases
Heat pump water heater	Commercial	Electric heat pump water heater with Btu out/in ratio of 3.9
Combined (interactive) measures	Commercial	Combination of envelope, HVAC, lighting, plug load measures

Our modeling assumes the same modest level of building end-use electrification as reflected in the Energy Information Administration's Annual Energy Outlook. Some regions, like the Northeast, have policies in place that will likely electrify loads at a faster rate than is reflected in our modeling. Because energy efficiency offers greater savings potential when electric loads are higher, the analysis in this report reflects the more challenging case for energy efficiency.

ENERGY EFFICIENCY IN AGGREGATE

Consideration of an aggregated set of energy efficiency measures should be part of any deep decarbonization or high renewable energy pathway study, but our research finds that this is not always the case. For this report, we reviewed an array of such studies to understand what role energy efficiency is expected to play in models of the clean energy transition. While all studies we reviewed reached the same general conclusion regarding the evolution of the electricity system (i.e., more solar and wind generation, less coal generation), many studies did not examine energy efficiency's potential role in depth.

However, pathway studies that do examine the role of energy efficiency find almost universally that energy efficiency is among the most important tools needed to realize our clean energy goals. For example, the International Energy Agency advises "a relentless focus on energy efficiency" to reach net-zero emissions by 2050. In the United States, the U.S. Department of State and the Executive Office of the President find that approximately 17% of the emissions reductions needed to reach net zero by 2050 will be achieved through energy efficiency measures. Regional pathway studies find that energy efficiency's role will be cost effective as well. A Massachusetts pathway study found that by 2050, "every dollar invested in efficiency returned $1.50 in avoided energy costs," while Los Angeles found that the combination of higher energy efficiency, electrification, and demand flexibility could reduce the cumulative costs of meeting clean energy goals by 13%.

Our modeling finds that energy efficiency measures reduce burdens on the power sector, avoiding billions of dollars' worth of energy and capacity costs in 2030, and 2–3 times as much in 2050 even with high deployment of renewable energy. We estimate that by 2050 annual power sector savings will range between $10 billion and $19 billion per grid region analyzed. Over the course of a year, approximately four-fifths of the value delivered to the electric grid by energy efficiency comes in the form of avoided energy costs that would otherwise be required to meet higher customer demand.

During days of highest demand, energy efficiency's primary benefit comes in the form of avoiding the need for additional power plants. In combination, energy efficiency measures can reduce the maximum annual load that must be met with nonrenewable sources by 31–46% in 2030 and 39–86% in 2050, where the actual reduction varies by region. These results hold regardless of the speed of renewable energy deployment, though we find that energy efficiency is likely to be more valuable in avoiding total electricity system costs under a more rapid supply-side decarbonization scenario.

By reducing demand, energy efficiency can also help mitigate many of the challenges associated with high levels of renewable energy deployment including critical materials mining, land acquisition, transmission siting, long renewable energy interconnection queues, and reliance upon unproven carbon capture and sequestration technologies.

ENERGY EFFICIENCY BY MEASURE

Energy-efficient practices and technologies take multiple forms, all designed to deliver equal or greater services with less energy. Examples of energy-efficient interventions include improving a building's thermal envelope (e.g., insulation, weatherization), upgrading heating and cooling systems, installing smart thermostats, replacing inefficient lighting with light-emitting diodes (LEDs), converting to heat pump water heaters, and upgrading appliances. Each measure delivers different benefits to both customers and the electric grid, and in ways that vary regionally.

This report analyzes the impact of 12 individual energy efficiency measures and packages in reducing annual energy, capacity, and environmental compliance costs in a high renewable energy future. We find that energy efficiency measures that affect thermal space conditioning loads are likely to have the greatest impact on both energy savings and avoided electricity system costs through 2050. However, the specific benefits will likely vary regionally (see figure ES-1). Savings will be larger in regions with lower baseline building energy codes, lower quality existing building stock, and more extreme temperatures, such as Texas and the Southeast.

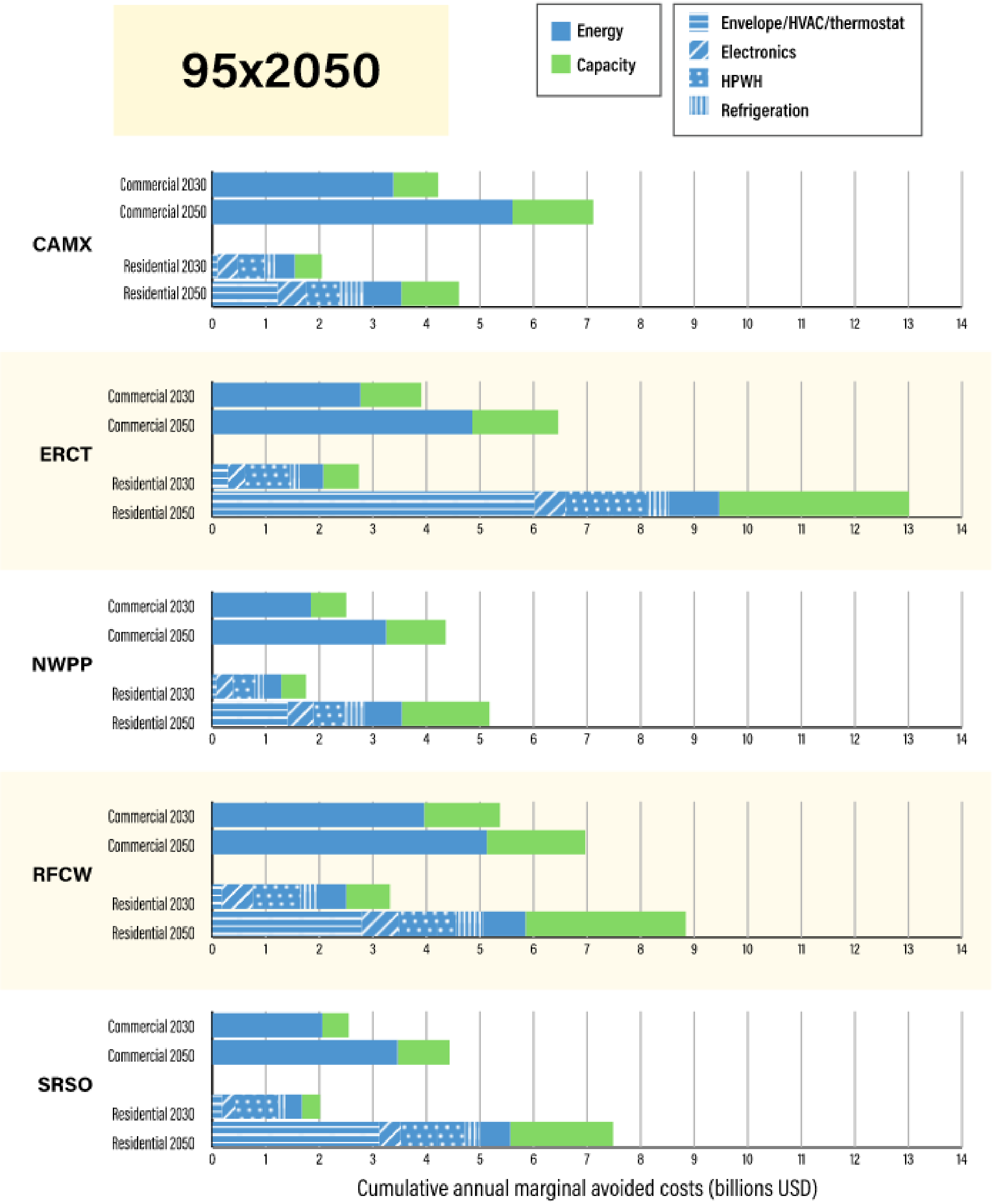

Figure ES-1. Approximation of annual energy and capacity costs the electric grid can avoid by virtue of energy efficiency measures in 2030 and 2050. Avoided costs are separated by residential and commercial sector and presented regionally (from top to bottom: California, Texas, Pacific Northwest, Midwest, and Southeast). The four residential measures/packages that deliver the greatest avoided energy cost savings (i.e., envelope/HVAC/thermostat, electronics, heat pump water heaters, and refrigeration) are noted individually. Avoided costs assume a high renewable energy future with an electricity system that linearly decarbonizes 95% by 2050.

We find that thermal space conditioning measures (HVAC improvements paired with envelope and thermostat upgrades) will benefit both the residential and commercial building sectors, though not in the same way. More near-term (i.e., through 2030) savings are projected for the commercial sector, with the residential sector comprising the greater share of savings by mid-century. This results from several trends, including the fact that over the next couple of decades, new commercial buildings are projected to be built at approximately twice the rate of new residential buildings, meaning there will be more near-term adoption of updated HVAC technologies in commercial buildings.

Among residential measures, switching from less efficient electric water heaters to heat pump water heaters consistently ranks among the top three in terms of avoided electricity system costs. Residential heat pump water heaters substantially reduce electric system costs through mid-century. Moreover, most water heaters have effective useful lifetimes that are short enough for stock turnover to play a positive role by 2030. Energy efficiency measures related to residential refrigeration, electronics, and clothes dryers have moderate potential to reduce electric system costs in 2030. These measures rise in relative importance to other measures through 2050.

RECOMMENDATIONS

Compared to utility-scale generation projects, energy efficiency measures can be deployed faster, at lower cost, and with greater geographic precision. The potential energy savings and avoided system costs are large, but those who deliver energy efficiency solutions will need to take advantage of limited opportunities to replace equipment—for example, end-of-life. Educational materials should be provided to customers well in advance of equipment's end of life to prime them to transition to more efficient heating and cooling technologies when the time comes for replacement.

To maximize electricity system benefits through demand-side interventions, utilities should prioritize thermal space conditioning measures within their portfolios. Replacing low-performance air source heat pumps or electric furnaces with high-performance air source heat pump models will guarantee savings and lower demand on the grid. This is especially true in regions like Texas and the Southeast that have a relatively high penetration of inefficient electric heating, drafty buildings, and warm climates.

The commercial sector has tremendous potential in this regard, especially over the next decade. Utility program designers should ensure they have robust integrated efficiency offerings for commercial buildings that simultaneously address heating, cooling, ventilation, insulation, lighting, plug loads, and energy management systems.

Utilities would also benefit from prioritizing heat pump water heater replacements for electric water heating customers, particularly in the residential sector. Heat pump hot-water heaters are the residential measure with the greatest potential savings in 2030 in both renewable energy scenarios we considered.

While those measures emerge as top priority items, utilities should continue to support all cost-effective energy efficiency, even if the energy savings and avoided costs are more modest. However, program administrators should be strategic to maximize long-term avoided costs in a transitioning grid. For example, measures with modest savings could be targeted as part of a larger package of efficiency upgrades. Administrators could consider scaling up incentives if measures such as pool pumps, consumer electronics, dishwashers, and clothes washers are upgraded simultaneously.

Finally, our literature review revealed that the vast majority of energy system modeling treats energy efficiency as an input assumption to the models, often as a decrement to load. This means that energy efficiency measures do not directly compete with renewable supply-side resources like wind, solar, and natural gas. Consequently, energy efficiency measures do not emerge from least-cost energy system optimizations as a resource of choice, which may reduce their procurement. Capacity expansion models should therefore ensure that all supply- and demand-side resources are fairly compared against each other, and not marginalized by default.

Background and Motivation

TOWARD AN EFFICIENT, DECARBONIZED FUTURE

There is widespread agreement that global greenhouse gas (GHG) emissions must be reduced to avoid the worst impacts of climate change. Myriad decarbonization pathways exist, but all serious efforts involve a substantial reduction in emissions from both the power and buildings sectors. In this report, we explore the crucial role of energy efficiency (EE) in achieving a high penetration of renewable power and the subsequent decarbonization of the electric power sector.

The United States has committed to reducing net GHG emissions by 50–52% below 2005 levels by 2030. As part of this commitment, the United States has set a supply-side goal of reaching 100% carbon-free electricity by 2035 (Department of State and Executive Office of the President 2021). In addition, net zero by 2050 targets have been set by 23 states, 15 of which have goals to procure 100% carbon-free electricity by or before 2050 (CESA 2023).

On the demand side, energy efficiency has the potential to cut U.S. GHG emissions from primary energy usage in half by 2050 (Nadel and Ungar 2019). As one of the lowest-cost and most effective resources to reduce energy demand, it is an essential tool for meeting climate goals.

While the role of energy efficiency is well established in global and economy-wide decarbonization efforts, its value proposition is positioned to change as the electricity consumption it offsets decarbonizes. Because solar and wind are carbon-free energy sources, energy efficiency has been perceived by some as a less valuable decarbonization tool in a high renewable energy future. For example, in its 2021 Power Plan, the Northwest Power and Conservation Council for the first time in recent years included less energy efficiency than previous plans as a result of more competitive, low-cost renewables (NPCC 2022).

In this report, we examine the role of energy efficiency in a decarbonized, high renewable energy future using two separate but complementary approaches. First, we conduct a literature review of existing deep decarbonization and renewable energy pathway studies with an eye to how energy efficiency has been valued in power sector modeling. Second, we conduct an analysis to estimate the electricity system savings if energy efficiency measures are aggressively pursued in the transition to a highly renewable electric grid. This analysis is conducted on a regional and measure-level scale in order to produce more granular policy recommendations. Expert interviews provided insight into the role of energy efficiency in a highly renewable future.

We begin by summarizing renewable energy and energy efficiency trends in our next subsections, *Growth of Renewable Energy* and *Evolution of Energy Efficiency*. Next, in the section *Energy Efficiency's Role in Pathway Studies*, we report on the results of our literature review of existing deep decarbonization and renewable energy pathway studies to better understand the role energy efficiency plays in power sector modeling experts' future grid scenarios. In *The Energy Efficiency Portfolio of the Future* section, we lay the groundwork for this portfolio by looking at specific energy efficiency measures and packages in detail, showing how each can avoid annual and peak-day electric system costs. We elaborate upon those findings in the *Discussion*, then offer *Energy Efficiency Measure Recommendations* for how grid planners and portfolio designers can best leverage energy efficiency to help create the decarbonized energy system of the future.

This report focuses on broad regional impacts. Though the deployment of renewable energy infrastructure and energy efficiency in a high renewable future involves important equity considerations, this report does not examine distributional effects. Targeted deployment of energy efficiency to low-income households or households that have otherwise been underserved by efficiency investments may improve energy affordability. Absent such targeted investments, these households may disproportionately bear the high system costs required to meet renewable goals (with or without broader efficiency deployment). Additionally, certain communities may experience different social and climate costs in the scenarios explored in our analysis. While these issues lie beyond the scope of the present report, we have included equity considerations where applicable in our policy recommendations below.

GROWTH OF RENEWABLE ENERGY

Electric generation from renewable sources has reached record high levels in the United States, currently accounting for approximately one-fifth of all generation and expected to exceed one-quarter in 2024. The increase in solar and wind generation is driving this growth. Between 2005 and 2020, solar and wind have grown from comprising just 5% of renewable energy generation to nearly 60% (EIA 2022c, 2023).[1]

The U.S. Energy Information Administration (EIA) projects that absent new policy, renewable electricity generation in the United States will grow more rapidly than overall demand, making up approximately 40% of the generation mix by 2050, as shown in figure 1 (EIA 2022a). However, this leaves a substantial continuing role for fossil fuels in electricity generation through mid-century.

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[1] This amounted to a record high of 32 GW of solar and wind capacity installed in the United States in 2020, followed closely by roughly 27 GW installed in 2021 (EIA (U.S. Energy Information Administration), 2022d).

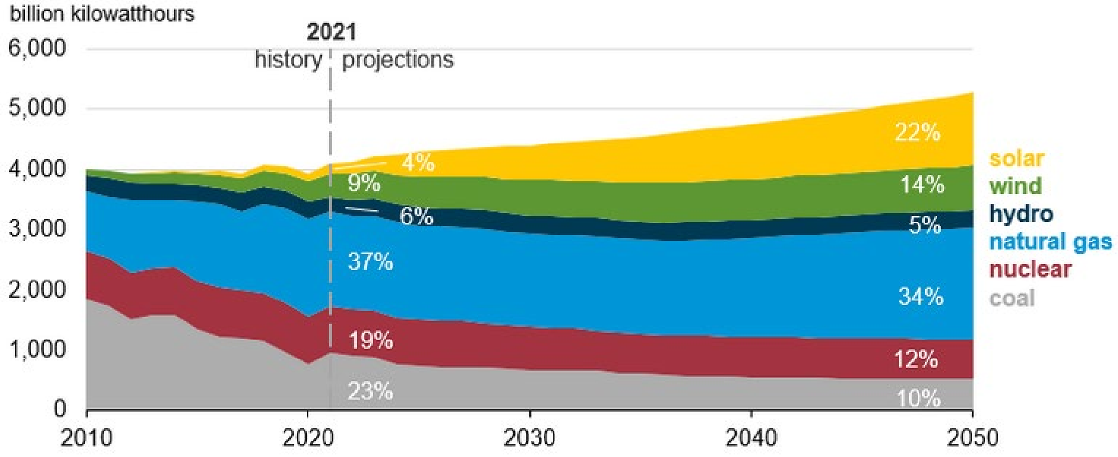

Figure 1. U.S. electricity generation from selected fuels according to EIA's Annual Energy Outlook 2022 Reference Case, which predicts U.S. generation mix absent new policy

This growth is not uniform. Some states, like California, have already at times been able to meet over 100% of consumer demand with renewable energy, while others, like West Virginia, produce and consume considerably less renewable energy (CAISO 2022). EIA's Annual Energy Outlook (AEO) projects how future renewable energy additions will vary by region, as shown in figure 2.

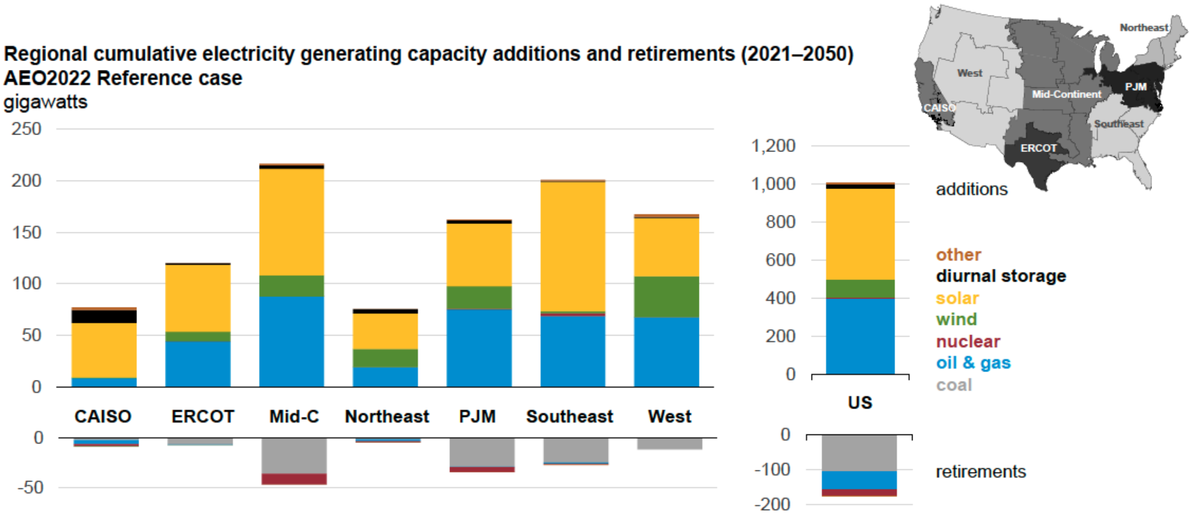

Figure 2. Regional cumulative electricity generating capacity additions and retirements according to EIA's Annual Energy Outlook 2022 Reference Case, which predicts U.S. generation mix absent new policy. The grayscale map shows the geographic location of the U.S. grid regions in the graph.

For the United States to achieve 90% carbon-free electricity by 2035, between 60–80 gigawatts (GW) of new clean capacity has to be added annually—absent new energy efficiency policy (see figure 3, for example). This is about double the current rate of renewable energy expansion. Moreover, because some renewable energy sources are variable, additional resources may be needed to ensure electricity is reliably available 24 hours per day, including daily energy storage (e.g., electrochemical batteries), seasonal energy storage (e.g., underground thermal), alternative fuels (e.g., renewable natural gas, green hydrogen), fossil-fuel generation with carbon capture and sequestration, and demand flexibility (i.e., direct demand reduction).[2]

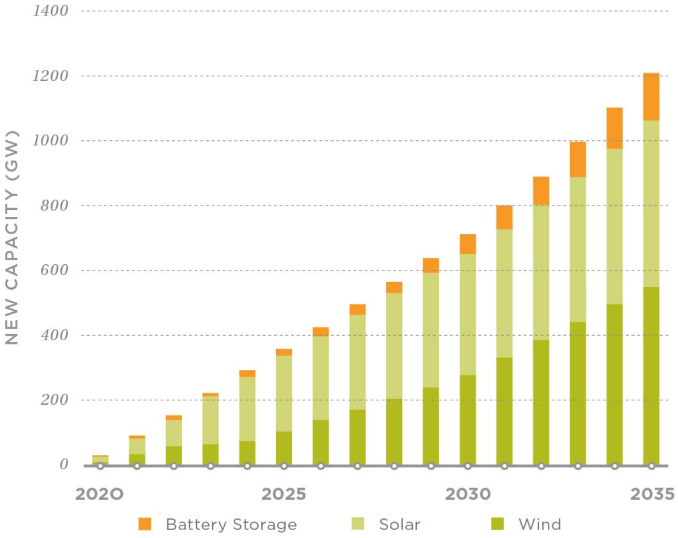

Figure 3. Cumulative new capacity additions under a scenario that leads to 90% clean electricity by 2035 from UC Berkeley's 2035 Report. Under this scenario, 1,100 GW of new wind and solar generation would have to be built by 2035. Source: Phadke et al. 2020.

EVOLUTION OF ENERGY EFFICIENCY

At its inception, U.S. energy efficiency policy was designed to reduce domestic demand for foreign oil in the context of the global energy crisis of the 1970s. By the 2000s, energy efficiency policy was touted as a low-cost way to address electricity reliability issues and price volatility that resulted from utility restructuring (Kushler, Vine, and York 2003). Energy efficiency has continued to offer utility benefits in the form of avoided electricity system energy, transmission, and distribution costs. A growing number of jurisdictions are additionally focusing on leveraging energy efficiency to cost effectively reduce emissions and deliver non-energy benefits (Specian and Gold 2021). [3,4]

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[2] These additional resources may have to grow even faster than renewable energy to meet deep decarbonization goals. For example, one estimate places the amount of battery storage required to meet a 90% clean energy by 2035 goal at 200 GW, which is roughly a 4,340% increase relative to the operational utility-scale battery storage capacity available in 2021 (Phadke et al., 2020).

[3] Almost half of U.S. states have set greenhouse gas emissions targets. According to the Smart Electric Power Alliance, 83% of U.S. customer accounts are served by an individual utility with a carbon reduction target, or a utility owned by a parent company with a carbon-reduction target, and 75% of U.S. customer accounts are served by a utility with a 100% carbon reduction target (SEPA (Smart Electric Power Alliance), 2022).

[4] Examples of non-energy benefits include improved health outcomes in buildings (e.g., by virtue of more airtight building envelopes), enhanced comfort, and resilience to low- or no-power situations (see, for example, the impacts of Winter Storm Uri in Texas in February 2021).

Though its most valued benefits have evolved over time, energy efficiency's most salient feature is arguably cost effectiveness, or its ability to deliver high benefits relative to its costs. While the methodology for calculating cost effectiveness varies by state, most frameworks accept that benefits accrue to some combination of energy efficiency program participants (i.e., homes and businesses), utilities (i.e., the grid), and society (indirectly). Participant benefits are derived from energy savings and other, non-energy benefits such as improved health outcomes and comfort. Many states also include a societal benefit of energy efficiency, which tries to capture positive impacts such as environmental preservation or economic development.

The transition to a highly renewable grid raises several questions about the future value of energy efficiency. First, the societal benefits, including greenhouse gas (GHG) mitigation, are less certain, as renewable energy resources comprise an ever-growing share of electric generation. Second, the cost of renewable energy has been plummeting in recent years and is expected to continue to fall, making it a highly competitive resource. For now, energy efficiency remains among the lowest-cost options for meeting grid needs—it can be procured for about 2.6 cents/kWh on average—but this may not remain the case as renewables saturate the market (Miller et al. 2021).[5]

Third, utility-run energy efficiency programs are facing challenges unrelated to the changing electric grid. In deciding which energy efficiency measures to offer to customers, utilities have preferred those that are (1) inexpensive, (2) easy to implement, and (3) deliver robust energy savings. The preferred efficiency measure over the past few decades has been lighting. But now that LEDs are a mature technology with high market saturation, partially as a result of longstanding utility programs and efficiency standards first set by the Energy Independence and Security Act of 2007, some wonder about the way forward for utility energy efficiency.

The growth of renewable energy and decarbonization goals provides one indicator. Energy efficiency goals have historically targeted annual electricity savings, but in a high renewable energy future, those goals are increasingly likely to be focused on reducing demand during the hours when the grid's carbon intensity is highest. These periods have coincided with each year's hours of highest total demand, which have historically occurred during hot summer afternoons with high air-conditioning loads. In a future that prioritizes decarbonization, though, it will be more important to reduce demand during periods of highest *net load*.[6] The predominant "all kilowatts are created equal" mentality of utility

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[5] For comparison, the projected levelized costs of onshore wind and solar coming online in 2027 are 3.8 cents/kWh and 3.6 cents/kWh, respectively, before accounting for tax credits (EIA (U.S. Energy Information Administration), 2022a).

[6] Net load equals the difference between total demand and variable (often renewable) energy production, or the amount of demand that still needs to be met by dispatchable generation.

energy efficiency resource standards will evolve toward a framework in which the timing of renewable energy generation influences the hours during which energy efficiency is most desirable.

Two additional demand-side management topics that deserve mention here are demand flexibility and beneficial electrification. Demand flexibility, or demand response (DR), refers to the modification of load in response to a grid signal, and can be applied during peak demand hours in order to maintain system reliability, or to match demand with fluctuating supply (such as intermittent renewables). Beneficial electrification is a form of energy efficiency that saves source energy by converting fossil-powered devices (e.g., gas furnaces, internal combustion vehicles) to more efficient electric versions (e.g., electric air source heat pumps, electric vehicles). While electrification is a key strategy for reducing *total* energy consumption and GHG emissions as generation sources switch to renewables, the act of switching fuels will add to electric system demand.

For example, if all fossil-fueled heating, water heating, and cooking loads were switched to less efficient electric alternatives in 2050, annual electricity usage nationally is projected to increase 1,081 TWh (33%) beyond the levels assumed in our modeling analysis. Daily net peak would correspondingly increase by 231 GW (49%) in winter and 64 GW (11%) in summer (Langevin et al. 2021).[7] This additional electric load could be significantly reduced via energy efficiency measures, making the savings estimates in this report conservative.

While both demand flexibility and beneficial electrification are important components of a decarbonized future, we will not explore them in greater detail in this report. Instead, we restrict our focus to the set of no-regrets energy efficiency measures that will exclusively lower electric system load.[8]

Methodology

This report is the result of literature review; quantitative modeling of the benefits of energy efficiency on the future, high renewable energy electric grid; and expert consultation. We began by identifying a set of prominent reports that lay out feasible pathways to achieve either a high renewable energy or deep decarbonization future. We conducted a literature review of those studies to better understand the role energy efficiency plays within them, the results of which we summarize in the section *Energy Efficiency's Role in Pathway Studies*.

Next, we conducted an analysis that quantifies the impact of individual energy efficiency measures on future electricity system costs by combining two datasets, each of which

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[7] According to that same analysis, load growth in winter could increase by as much as 353 GW if heat pumps exhibit particularly poor low-temperature performance.

[8] There will be some limited, specific violations of this goal, such as efficient electric heat pumps that slightly increase electric system load during hours when they switch into backup electric resistance heating mode.

projects future hourly energy system values at a regional level across the United States. One dataset focuses on individual demand-side measures, while the second projects supply-side avoided costs.

We analyze those data to better understand which energy efficiency measures or packages will be most effective at avoiding specific electricity system costs in 2030 and 2050. We consider avoided energy, capacity, and environmental compliance costs in this analysis. To understand how these results vary across the United States, we focus our analysis on five regions: California, Texas, the Southeast, the Midwest, and the Northwest.[9] To understand how the rate of renewable energy deployment impacts our results, we study two renewable energy scenarios — one in which the U.S. power sector mostly decarbonizes by 2050, and another in which it mostly decarbonizes by 2035. The results of that analysis are presented in the section "Demand-Side Measures within the Standard Scenarios."

We also interviewed a handful of experts on renewable energy, energy efficiency, grid planning, and energy system modeling. These experts provided a complementary perspective to our literature review, offering their own insights into the evolution of energy efficiency and renewable energy. A subset of these experts also reviewed our quantitative analysis, providing their own explanations for our scenario results and offering recommendations for steps that energy efficiency portfolio designers and grid planners should take to ensure energy efficiency is fully and effectively utilized as a tool to enable a reliable, low-cost renewable energy future. Much of their input is reflected in the *Discussion* section.

Energy Efficiency's Role in Pathway Studies

In recent years researchers have invested great effort in charting out plausible pathways that society can take to meet its energy and climate goals. The specific purpose of each *pathway study* may vary. Some are concerned with achieving a target percentage of renewable energy generation by a certain year, while others detail how to mostly or fully decarbonize major economic sectors.

Despite these differences, pathway studies share common features useful for our purposes. They incorporate real-world data to clarify how quickly a city, state, region, nation, or the world could install low-carbon technologies. They usually involve optimization that solves for lowest-cost solutions subject to constraints that guarantee particular energy or climate goals are met by certain years. And they often consider the impact of a range of variables and sensitivities to account for various types of uncertainty that impact the energy system.

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[9] These five regions were selected to take advantage of granular EE data made available through public data release by Langevin et al. (2021). While the Northeast was not included in those data, ACEEE has published *Demand-Side Solutions to Winter Peaks and Constraints*, a report that quantifies the grid benefits of various distributed energy resources in a highly electrified New England in 2040 (Specian, Cohn, and York 2021).

Broadly speaking, these pathway studies address energy efficiency in one of two ways. They either assume a baseline level of efficiency that would exist absent new policy intervention, or they assume ample energy efficiency in the form of an aggregated decrement to load, the remainder of which must be met by conventional supply-side resources.

Regarding the former case, one literature review of clean energy pathway studies notes that, of the 11 studies reviewed, "The models generally did not assume high levels of energy efficiency, greater reliance on demand response (including vehicle-to-grid integration), or the development of longer-duration energy storage—all of which would reduce the capacity buildout required in these transitions" (Esposito, 2021). These studies often rely on default demand forecasts, like the EIA Annual Energy Outlook Reference Scenario, that only consider business as usual energy efficiency policies, rather than explore the possibilities if energy efficiency was pursued to its full potential.

In the latter case, energy efficiency inputs are exogenous to the model. In other words, energy efficiency is not compared directly to wind, solar, natural gas, storage, or other energy resources, which limits the potential for energy efficiency to emerge as a primary resource worthy of procurement alongside conventional generation.[10]

The pathway studies we reviewed all reached common conclusions on how to meet decarbonization constraints. By 2050 the electric grid could decarbonize by installing more wind and solar generation, retiring aging coal plants, and ramping down natural gas plants. To accommodate renewable energy's variability issues, this transition would require some combination of increased renewable energy capacity, sufficient transmission infrastructure to carry it to market, energy storage, and varying degrees of carbon capture technologies to allow limited continued usage of fossil fuels when renewable energy is unavailable.

In the remainder of this section, we review a set of global, national, and regional pathway studies to better understand the role that decarbonization and clean energy modeling experts expect energy efficiency to play in the transition. While no single modeling effort should be relied on exclusively, the *set* of pathway studies provides a more comprehensive perspective on the costs of achieving climate and energy goals with and without energy efficiency.

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[10] One exception to this broad observation of pathway studies is the modeling done by Vibrant Clean Energy (VCE). VCE's WIS:dom-P model uniquely considers distributed energy resources (including EE) as endogenous factors (Clack et al. 2020). Some utilities evaluate energy efficiency as a resource in their Integrated Resource Plans, but these plans are typically limited to regional climate goals and shorter time horizons than the pathway studies discussed here (Frick et al. 2021).

GLOBAL PERSPECTIVE

The International Energy Agency (IEA) publishes an annual World Energy Outlook (WEO) that models a set of different global energy and decarbonization scenarios. WEO's Net Zero Emissions by 2050 Scenario (NZE) is a narrow but achievable pathway to stabilize average global temperature increase at 1.5°C. WEO projects that renewable energy is poised to become the foundation of electricity systems throughout the world, expanding at a rate commensurate with the growth of electricity demand. IEA cites factors such as low costs, widespread availability, and policy support as driving a tripling of renewable energy capacity in order to achieve a 30% share of global generation over the next decade.

However, a substantial "ambition gap" remains between current policy trajectory and what is needed to reach net-zero emissions by 2050 (i.e., between the NZE scenario and a Stated Policies Scenario that is limited to existing and forthcoming policies). The WEO identifies key measures that can collectively help close that gap, including "a massive additional push for clean electrification" and "a relentless focus on energy efficiency." Although annual energy intensity improvements were expected to reach 2% in 2022, this still lags the 4% needed each year through 2030 to realize the NZE scenario (IEA (International Energy Agency), 2022).[11] According to WEO modeling, investments in energy efficiency can help reduce the energy intensity of global demand by more than 4% by 2030. These measures are particularly important within the buildings, industrial, and transportation sectors.

In 2030 total global energy consumption would be about 30–75% higher without the modeled energy efficiency investments, making the task of decarbonization considerably more costly and difficult.[12] IEA encapsulates these findings, writing, "Focusing on energy efficiency action is the unambiguous first and best response to simultaneously meet affordability, supply security and climate goals"; energy efficiency should be considered the "first fuel of all energy transitions." IEA further notes that due to load growth in emerging countries, the largest energy efficiency opportunities are likely to be found in countries like Brazil, China, India, Indonesia, Mexico, and South Africa (IEA (International Energy Agency), 2022).

The International Renewable Energy Agency (IRENA) has also conducted an analysis quantifying the contributions of EE and renewable energy to global decarbonization, focusing on five countries: the United States, Japan, India, Germany, and China. IRENA found that in combination, EE and renewable energy have the potential to reduce carbon emissions 90% of the way toward an average global temperature increase of 2°C (see figure 4) while

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[11] The IEA defines energy intensity as the "ratio of global total energy supply per unit of gross domestic product (GDP)" and uses this as a rough proxy for energy efficiency.

[12] Total final consumption is projected to be three-quarters higher in 2030 in the Announced Pledges Scenario than the NZE Scenario without efficiency improvements.

simultaneously reducing overall energy system costs (IRENA (International Renewable Energy Agency), 2017).

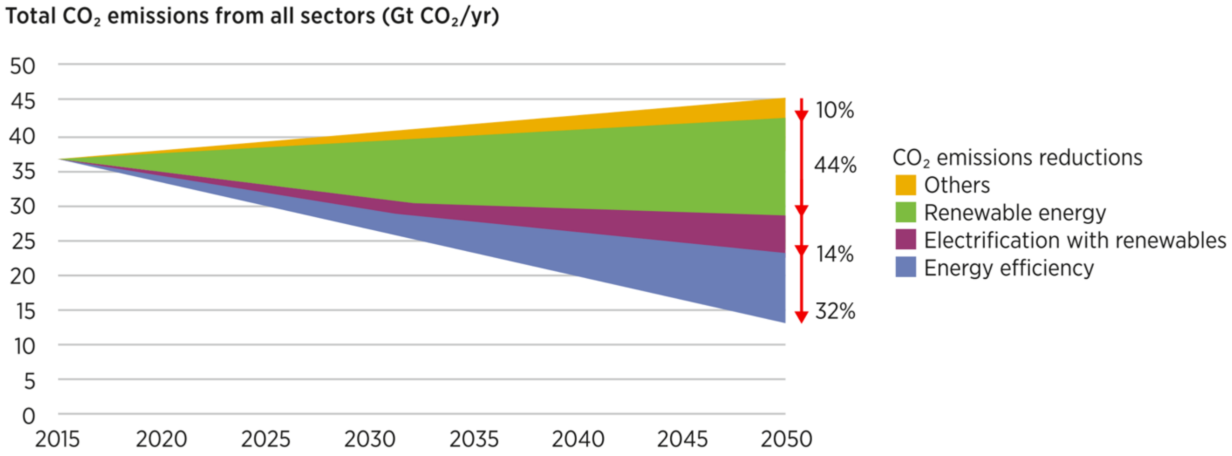

Figure 4. Total projected global CO_2 emissions (all sectors) through 2050 (gigatons of CO_2 per year) along with the assumed reductions generated by renewable energy, electrification, and energy efficiency. Source: (IRENA (International Renewable Energy Agency), 2017).

The IRENA study further argues that there is a synergistic relationship between EE and renewable energy. Accelerated deployment of renewable energy encourages beneficial electrification for the purpose of decarbonization, which lowers primary energy demand and increases overall efficiency. And because renewable energy is usually the first, least expensive generation resource to be deployed, reducing overall demand through energy efficiency further increases the share of electricity provided by renewable energy.

Another study led by Stanford University modeled pathways for 139 countries to achieve electric grids powered entirely by wind, solar, and hydroelectric resources. The study reports that “modest additional policy-driven energy efficiency” results in a 7% reduction in load and a 160 GW reduction in required capacity in the United States. This would equate to roughly $400 billion in avoided capital costs by 2050 (Jacobson et al., 2017).[13]

NATIONAL PERSPECTIVE

The set of national-scale pathway studies reviewed for this report demonstrate mixed results with respect to their handling of energy efficiency (see table 1). Some studies implicitly ignore energy efficiency’s potential by assuming business as usual (i.e., no policy intervention) baseline conditions, opting instead to focus primarily on supply-side interventions. Consequently, these studies do not report a prominent role for energy efficiency in a clean energy future. The studies that do intentionally investigate energy efficiency’s role generally reach a different conclusion—that not only is energy efficiency

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[13] Globally, they project $3.5 trillion in avoided capital costs by 2050.

valuable, but it is in fact a critical component of our clean energy future. However, these studies generally do not isolate the impacts from energy efficiency or investigate the measure-level implications.

Table 1. Select collection of national-scale pathway studies reviewed for this report, complete with each study's primary objective and handling of energy efficiency (EE)

Study Name	Goal	Energy efficiency considered?
Net-Zero America (Larson et al.)	Net-zero emissions by 2050	Yes. Study assumes adoption of most efficient equipment at end-of-life replacement in the buildings sector, plus aggressive industrial productivity improvements and reductions in aviation energy use; additional scenarios include varying degrees of electrification.
The Long-Term Strategy of the United States (U.S. DOS)	Net-zero emissions by 2050	Yes. Study assumes EE gains in the transportation, buildings, and industrial sectors. Study provides examples of EE measures and quantifies their emissions impact, but does not include data or analysis sufficient to quantity the magnitude of EE deployment.
The Biden Administration Must Swiftly Commit to Cutting Climate Pollution at Least 50 Percent by 2030 (NRDC)	53% emissions reduction by 2030; net-zero by 2050	Yes. Study assumes a little over 1% of existing buildings undergo deep envelope retrofits each year; building equipment and appliances replaced with highest efficiency commercially available products at time-of-replacement. Industrial energy intensity assumed to drop 1.05% annually between 2020 and 2050.
2035 Report (Phadke et al.)	90% carbon-free electricity by 2035	No. No energy efficiency beyond baseline AEO2020 considered (which anticipates only modest gains in energy efficiency). However, study mentions that EE/DR could help curtail projected use of natural gas in peak hours.
Robust Decarbonization of the U.S. Power Sector: Policy Options (Stock and Stuart 2021)	80% emissions reduction by 2035	No. No incremental energy efficiency considered beyond the baseline assumptions baked into the National Renewable Energy Laboratory's (NREL) Standard Scenarios. Study instead prioritizes impacts of overall demand, fuel prices, and technology costs.

Sources: (Larson et al., 2021; NRDC (National Resources Defense Council), 2021; Phadke et al., 2020; Stock & Stuart, 2021; US DOS (United States Department of State) & Executive Office of the President, 2021).

The Net-Zero America study assumes all efficiency technologies must be commercially available at scale, and must be able to satisfy a fixed demand for energy services. In the study, energy efficiency is implemented by replacing equipment or appliances at the time-of-replacement with the same-fuel most efficient option within the building sector. The study concludes that "End-use efficiency improvements and electrification across all sectors are critical for reducing the required build out of the energy-supply system to deliver the energy needed to meet the given level of energy service demands." The study admits that the more aggressive option of engaging equipment replacements before economic end-of-life remains possible, but would increase transition costs (Larson et al., 2021). Unfortunately, this study does not model impacts *without* energy efficiency, which negates any opportunity for comparison with this alternative future.

A pathway study jointly produced by the U.S. Department of State (U.S. DOS) and the Executive Office of the President identifies multiple pathways to realizing a net-zero economy by 2050. The authors cite five key transformations that occur in all modeled pathways. The three most relevant to this report are decarbonizing electricity, electrification, and energy efficiency. We share a chart from that report in figure 5 below.

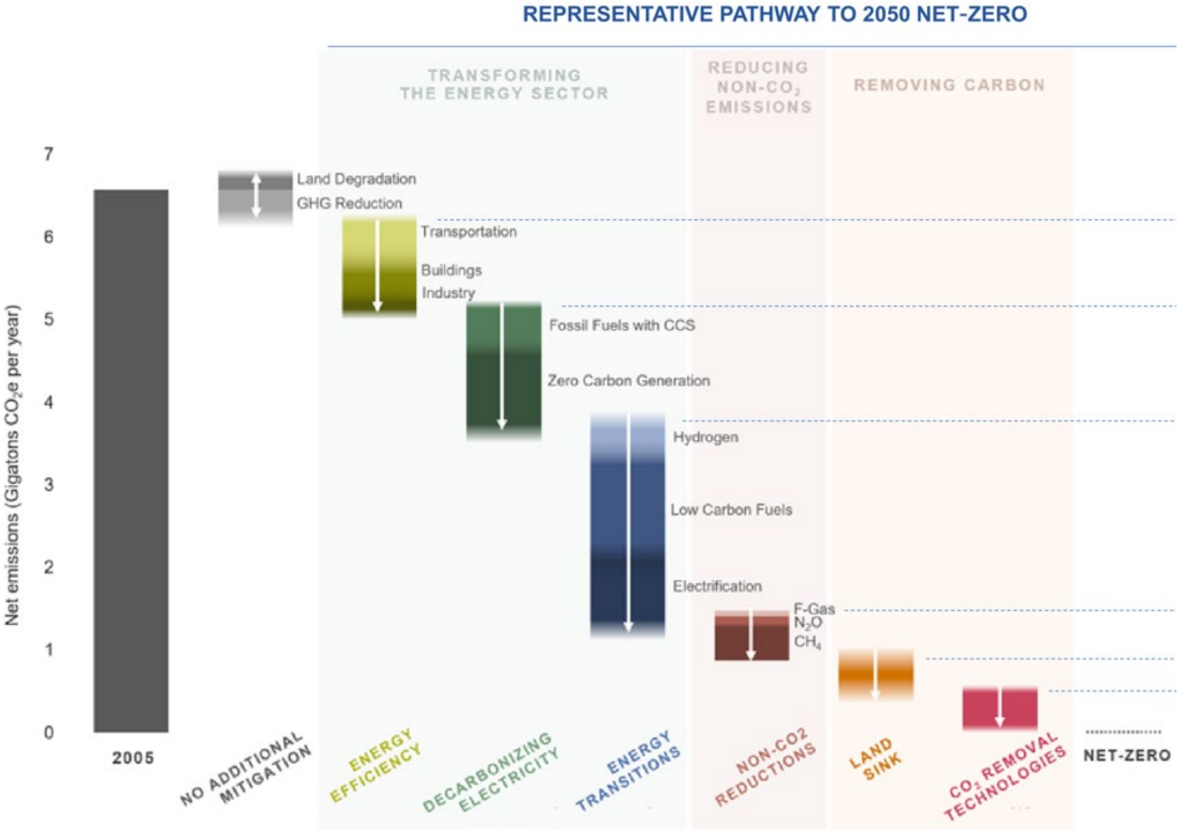

Figure 5. Emissions reductions pathways to achieve 2050 net-zero emissions in the United States. The three elements under "Transforming the Energy Sector" are (from left to right) energy efficiency, clean electricity

production, and electrification of fossil-fueled end uses. Source:(US DOS (United States Department of State) & Executive Office of the President, 2021).

By their modeling, approximately 4.5 gigatons of the 6.5 gigatons emissions reductions needed to reach net zero will come from transforming the energy system, that is, decarbonizing electricity generation and shifting to renewable energy. Approximately 17% of the emissions reductions needed to reach net zero will be achieved through energy efficiency measures such as improved building insulation and HVAC performance, and more efficient electronics. Because much of the equipment in need of upgrades have long lifetimes, the report says, "The priority this decade is to rapidly improve energy efficiency and increase the sales share of clean and efficient electric appliances" (US DOS (United States Department of State) & Executive Office of the President, 2021).

Another national study from the National Resources Defense Council (NRDC) and Evolved Energy Research (EER) reaches a similar conclusion: "[A] 53 percent net GHG reduction target by 2030 is technologically feasible and can be achieved by relying on the three well-established decarbonization pillars—energy efficiency, clean energy, and end-use electrification" (NRDC (National Resources Defense Council), 2021). The report shows that a 55% reduction in CO_2 emissions can be achieved by 2030 with a combination of clean generation (61%), transportation efficiency (23%), industrial efficiency (13%), and buildings efficiency (3%).

This study also identifies specific measures that can help realize CO_2 reductions across those sectors. These include zero-emission vehicle targets, electric vehicle tax incentives, and charging infrastructure build-out in the transportation sector; improved appliance efficiency standards, electrification incentives, and weatherization in the buildings sector; and incentives for efficient, electrified technologies in the industrial sector. This study notes that emissions reductions in the buildings and industrial sectors are expected to further increase after 2030.

A Harvard-led study on achieving 80% decarbonization of the electric system by 2035 fails to consider demand-side measures beyond the basic assumptions in NREL's Standard Scenarios (Stock & Stuart, 2021). Similarly, the University of California Berkley's 2035 Report models pathways to achieving 90% carbon-free electricity by 2035 without any modifications to the Annual Energy Outlook's business as usual demand-side assumptions. Notably, the Berkeley report includes existing natural gas capacity to meet the remaining 10% of electricity demand to avoid more expensive renewable energy and long-duration storage capacity, but notes that "Other technology alternatives not considered in this analysis, such as demand response, energy efficiency, or flexible load, may be more cost-effective for system balancing in those hours" (Phadke et al., 2020).

Although it is not technically a pathway study, we also explored the projected generation and capacity requirements for the U.S. energy system through 2050 using the NREL

Standard Scenarios.[14] We looked at two scenarios in particular—95x2050 and 95x2035—that require 95% decarbonization of national electric generation by 2050 and 2035, respectively, to represent a high renewable energy future.[15] None of the available sensitivity analyses specifically modulate the assumed level of demand-side energy efficiency, so we use the *low demand growth* and *high demand growth* side cases as proxies for *high energy efficiency* and *low energy efficiency*. In the 95x2050 scenario, the difference between these two cases is equivalent to saving 6.2 million GWh of energy between 2022 and 2050, or an average of 8% annually (see figure 6).[16]

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[14] More background on the Standard Scenarios is provided in the section "Demand-Side Measures within the Standard Scenarios."

[15] The 95x2035 scenario scales up to 100% decarbonized electricity by 2050.

[16] The high/low demand growth cases are based off the EIA AEO 2021 high/low economic growth scenarios. We note that an 8% average annual reduction in demand is relatively consistent with other energy efficiency scenarios, if not somewhat high. For example, the *moderate scenario* displayed in figure 7 assumes an average reduction in building energy demand of roughly 5% between 2022 and 2050.

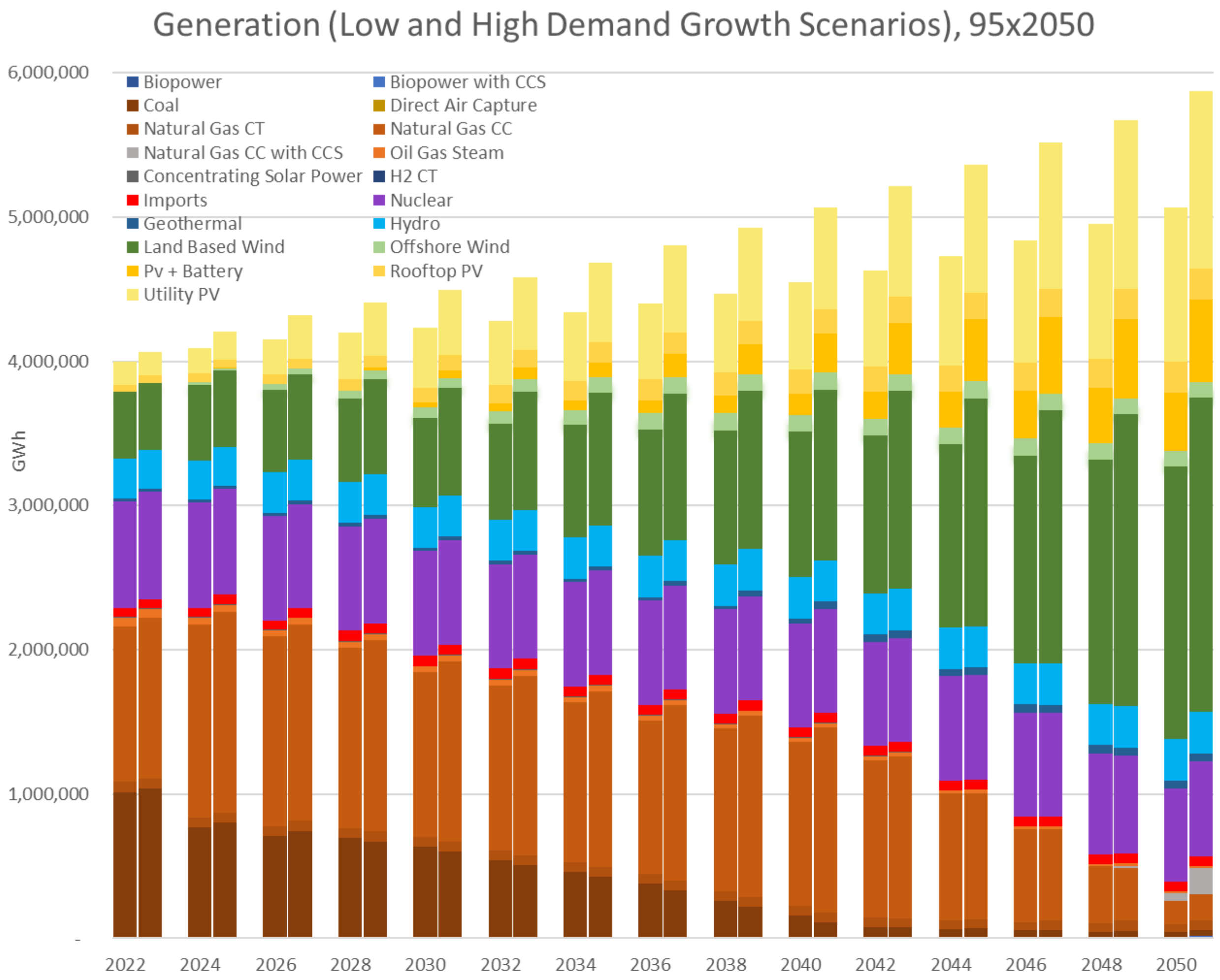

Figure 6. Projected U.S. generation requirements for meeting a 95% electric decarbonization by 2050 goal. Results are presented every two years with low demand (high efficiency) presented on the left and high demand (low efficiency) presented on the right. Data sourced from Cambium via the NREL Standard Scenarios.

Lowering demand through 2050 will meaningfully impact the amount of additional capacity needed to meet electric needs. Comparing annual capacity needs between low and high demand growth scenarios for the 95x2050 scenario shows that additional capacity would be needed across most resource types, along with marked increases in specific technologies such as carbon capture and sequestration and direct air capture. In 2050 alone, higher demand results in the need for an additional 330,000 MW of capacity, including an additional 62,700 MW of natural gas, 76,228 MW of land-based wind, 17,763 MW of battery, and over 130,000 MW of additional solar capacity. Most notably, the high demand growth scenario requires more than triple the amount of natural gas capacity paired with carbon capture and sequestration, and more than four times the amount of direct air capture. Capacity requirements for the 95x2050 scenario and generation and capacity requirements for the 95x2035 scenario are available at the end of “Appendix B–Additional Results.”

REGIONAL PERSPECTIVE

Although we discovered fewer detailed regional pathway studies, those we did review generally evaluated energy efficiency in greater detail than did the national or global studies, though consistently as an exogenous factor (see table 2).

Table 2. Select collection of regional-scale pathway studies reviewed for this report, with each study's primary objective and handling of energy efficiency

Study name	Goal	Energy efficiency considered?
Achieving 100 Percent Clean Electricity in California	100% electricity retail sales and state loads from renewable and zero-carbon resources by 2045	**Yes (in part)**. Energy efficiency is included in the baseline, but its effects are not isolated.
Los Angeles 100% Renewable Energy Study	100% renewable energy by 2045	**Yes.** LA100 considers multiple futures with varying degrees of customer electricity demand. The *Moderate* future assumes electrification and moderate improvements to energy efficiency. The *High* future assumes customers adopt the most efficient technologies available when purchasing equipment.
Massachusetts 2050 Decarbonization Roadmap	Net-zero emissions by 2050	**Yes.** Multiple customer electricity demand futures are considered, each of which varies assumed levels of energy efficiency, electrification, and demand flexibility.

Massachusetts conducted a detailed pathway study with the goal of achieving net-zero emissions economy-wide by 2050. Similar to other global and national pathway studies, the modelers found that three of the strategies common to all net-zero pathways were increased energy efficiency, electrification, and decarbonizing electricity. When considering the lowest cost transition for the state, EE was found to be the primary driver of emission reductions in the near term, while high levels of electrification and greater deployment of offshore wind generated further reductions in the medium term.

The Massachusetts study team also found that energy efficiency played an important role in keeping supply-side infrastructure costs low. In their modeling, reduced energy efficiency deployment led to a 50% higher offshore wind build from 2030 to 2045. They also found that energy efficiency measures will become more valuable over time as carbon emissions limits become more stringent. By 2050, "Every dollar invested in efficiency returned $1.50 in avoided energy costs" (Ismay et al., 2020).

The California Energy Commission (CEC), California Public Utilities Commission (CPUC), and California Air Resources Board (CARB) produced a joint analysis that explores pathways to meet the requirements of California Senate Bill 100. SB100 requires that California supply 100% of retail electricity sales by renewable and zero-carbon resources by 2045. The study examines a wide variety of clean energy options and finds that "Prioritizing cost-effective energy efficiency measures remains critical as the state moves toward 100 percent clean electricity." The joint research team reports that EE reduces the need for additional capacity, reduces land use and environmental impacts, and saves customers money (CARB (California Air Resources Board) et al., 2021).

The Los Angeles 100% Renewable Energy Study (LA100) is one of the more ambitious and rigorous renewable energy pathway studies. The study's multidisciplinary research team considered many elements including customer demand, distributed energy resources (such as energy efficiency, demand response, and rooftop solar), renewable generation, storage, the distribution system, reliability, GHG emissions, air and health quality, environmental justice, economic impacts, and jobs. LA100 also considers an "SB100 scenario," which is based on California Senate Bill 100.

LA100 reports that the combination of higher energy efficiency and demand flexibility—a *High* scenario—reduced cumulative costs by 13%, relative to a *Stress* scenario with lower levels of energy efficiency and demand flexibility (Cochran et al., 2021). The former scenario also resulted in lower electricity prices, reduced emissions, and operational benefits as a result of increased flexibility.

POWER SYSTEM IMPLICATIONS

In this section, we describe some additional themes that emerged from the studies we reviewed regarding the benefits that energy efficiency can deliver to the power system in a high renewable energy future. Mostly or totally decarbonizing electricity generation introduces new challenges in a variety of areas.

The transition to a clean energy economy will require significant additional investments in generation and transmission infrastructure. Meeting 100% of electricity demand with renewable energy by 2050 may require solar and wind capacities that are 39 and 28 times larger than today, respectively (Larson et al., 2021). Because renewable energy is non-dispatchable, high amounts of it require larger reserve margins to maintain reliability. ISO-NE, for example, predicts its reserve margins may need to increase up to 300% by 2040 to keep the system online in times of stress (ISO New England, 2022). In the Northwest, new transmission infrastructure will need to be built to move renewable energy generated primarily east of the Cascade Mountains to population centers west of the Cascades, raising important siting and cost concerns (Flatt 2023).

Energy efficiency can play a significant role in reducing the generation and transmission capacity needed to meet future demand. The combination of efficiency improvements in the building, industrial, and light-duty vehicle sectors (e.g., reduced vehicle miles traveled) could collectively lower demand in the United States in 2040 by 20%, or approximately 2,000 TWh (Larson et al., 2021). A separate analysis from NREL finds that lowering demand growth leads to a \$307–\$506 billion (or 16–19%) reduction in capacity investments, and a 2–15% reduction in annual system costs (Denholm et al., 2022). And the Intergovernmental Panel on Climate Change notes that CO_2 removal (e.g., carbon capture and storage, afforestation) is needed less in pathways with a particularly strong emphasis on energy efficiency and low demand (Rogelj et al., 2018).[17]

Most energy efficiency measures are deployable on much faster timescales and with finer geographic precision than utility-scale generation, which helps mitigate challenges associated with the latter (Clune et al., 2020). And large-scale energy efficiency programs may face lower obstacles compared to the challenges of a large-scale supply-side transition. These challenges include mining for critical materials and supply chain issues (Dehghani-Sanij et al., 2019; Holzman & Waldman, 2022); land acquisition to site solar farms, wind farms, and transmission lines (CARB (California Air Resources Board) et al., 2021; Phadke et al., 2020); and lengthy interconnection queues ((LBNL (Lawrence Berkeley National Laboratory), 2020).[18] Speed matters. The damage to the climate by GHG is cumulative and—all else being equal—emissions reductions today are more valuable than emissions reductions in the future (Hibbard et al., 2020).

Though high electrification scenarios are not considered in depth in this study, the transition to a clean energy future will require electrification, which will incur additional costs on the distribution and transmission systems. While the cost of distribution system upgrades is more difficult to ascertain, primarily due to a lack of available data, the LA100 study estimates distribution system costs of \$472 million (about 1–2% of bulk system costs) just to

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[17] Many deep decarbonization pathway studies rely on negative emissions technologies, particularly for reaching the final few percent needed to achieve a 100% clean energy system. Carbon dioxide removal technologies remain unproven at scale, however. In 2021 the United States had the capacity to capture roughly 0.004 gigatons of CO_2, a far cry from the 0.7–1 gigatons estimated to be necessary to meet Paris Agreement targets (Smith et al. 2023; Gonzales, Krupnick, and Dunlap 2020).

[18] The interconnection problem has become so great in PJM that the Mid-Atlantic grid operator has proposed a two-year freeze on new proposals to allow it to clear its existing application backlog (Thomas 2022). In addition to causing delays, the tremendous growth of the interconnection queue has been shown to occur in parallel with substantial interconnection cost increases (Seel et al. 2023).

integrate the distributed energy resources required to meet their decarbonization goals.[19] Energy efficiency measures can be targeted to areas on the grid that are projected to suffer the most from congestion issues, mitigating the need for expensive distribution system upgrades. For example, Consolidated Edison's 2016 Brooklyn-Queens Demand Management project allowed the utility to defer a $1.2 billion substation upgrade by contracting 52 MW of demand reductions (as well as 17 MW of distributed energy resources) (ConEd 2023).

The Energy Efficiency Portfolio of the Future

While efficient lighting measures have historically constituted a significant fraction of savings from energy efficiency portfolios, in recent years other factors—including breakthrough technologies, technology price declines, the drive toward decarbonization, and the premium placed on flexible, grid-interactive technologies[20] —have, in combination, advanced our concept of energy efficiency. Despite these changes, there has been a dearth of research into the roles of individual efficiency measures in reducing electric system costs. In this section we share our methodology for more granularly quantifying how individual energy efficiency measures and packages can avoid annual and peak-day electricity system costs in a high renewable energy future.

DEMAND-SIDE MEASURES WITHIN THE STANDARD SCENARIOS

In order to analyze the impact of individual electric energy efficiency measures and packages for reducing annual energy and capacity costs in a high renewable energy future we consider two separate high renewable energy futures: one in which the U.S. power sector emissions are mostly eliminated by 2050, and a more ambitious case where they are mostly eliminated by 2035.

Our residential and commercial demand-side measures were generated in Scout, a software tool developed by Lawrence Berkeley National Laboratory (LBNL) and the National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy for estimating the energy impact of various energy conservation measures on the U.S. building stock. These measures are summarized in table 3 and described in greater detail in "Appendix A–Quantitative Analysis Additional Details." Each measure has 8,760 hourly load shapes provided for 2030 and 2050, the two years we examine in this analysis.

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[19] The distribution costs did "not include substantial investments required to address current distribution upgrade needs, routine maintenance of the distribution system, distribution operations costs, or land acquisition and other costs that may be required for distribution upgrades, notably for substation upgrades. Collectively these other costs are likely much higher than these additional costs required as a result of load changes and distributed energy resource (DER) adoption."

[20] Grid-interactive building technologies include smart technologies and on-site distributed energy resources capable of providing demand flexibility while co-optimizing for energy cost, grid services, and occupant needs and preferences in a continuous and integrated way (Satchwell et al. 2021).

Table 3. List of residential and commercial energy efficiency measures modeled in our analysis and in Langevin et al. (2021)

Measure	Sector	Definition
Envelope/HVAC/thermostat	Residential	Envelope improvements (i.e., wall insulation, foundation insulation, windows), Internet-connected thermostat, plus HVAC upgrade (where applicable)
Heat pump water heater	Residential	80-gallon electric heat pump water heater with 2.4 coefficient of performance
Clothes dryer	Residential	Ventless heat pump dryer with CEF = 3.65
Electronics	Residential	Plug loads usage level halved
Refrigeration	Residential	EF 22.2 refrigerator
Lighting	Residential	LEDs, 112 lumens/Watt
Pool pump	Residential	0.75 horsepower pump with 1,688 kWh annual energy use
Clothes washer	Residential	ENERGY STAR Most Efficient (IMEF ≥2.92)
Dishwasher	Residential	Rated 199 kWh/year
Refrigeration	Commercial	Various minimum performance levels for reach-in freezers, walk-in freezers, reach-on refrigerators, walk-in refrigerators, and supermarket display cases
Heat pump water heater	Commercial	Electric heat pump water heater with Btu out/in ratio of 3.9
Combined (interactive) measures	Commercial	Combination of envelope, HVAC, lighting, plug load measures

To assess the demand-side impact of these measures, we first establish a baseline load shape that assumes the same level of energy efficiency as is present in the Annual Energy Outlook. We then compare this to an efficient load shape that assumes that measures in table 3 have been gradually adopted beginning in their market entry year of 2017, subject to Scout's stock turnover assumptions.[21] Note that in these data, no mix of supply-side

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[21] Scout's "maximum adoption" scenario assumes that efficiency measures are applied to all new construction and existing measures at the end of their useful life. Typical technology lifetimes are taken from EIA. Envelope and Internet-connected thermostat upgrades occur at the same rate as the HVAC replacement rate. No early retrofits are assumed.

resources is represented. The only constraint is from stock turnover rates, and the best available technologies represented here are always adopted. Hourly savings are calculated by taking the difference of the baseline and efficient load profiles.

To assess the supply-side of these transitions we utilize the 2021 Standard Scenarios developed by NREL (Cole et al. 2021). These scenarios represent plausible grid evolution pathways under a variety of assumed constraints and conditions.[22] In 2021 NREL created 50 power sector scenarios for the contiguous United States, some of which are summarized as part of our literature review in the section "Energy Efficiency's Role in Pathway Studies." A small subset of these Standard Scenarios are expanded upon as part of NREL's Cambium tool (Gagnon et al. 2021). Each scenario within this subset has published hourly emission, cost, and operational data every two years from 2022 through 2050 under least-cost hourly dispatch assumptions.[23] The Cambium cost metrics (all measured in $/MWh) of interest for our present analysis are:[24]

> **Energy cost**: marginal cost of the additional energy to serve an increase in end-use load
>
> **Capacity cost**: marginal cost of the additional firm generation capacity and transmission infrastructure needed to maintain resource adequacy when end-use load is increased

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[22] The Standard Scenarios are generated using the Regional Energy Deployment System (ReEDS) long-term capacity expansion model; the Distributed Generation Market Demand Model (dGen), which estimates the growth of distributed generation resources (e.g., rooftop solar); and PLEXOS, a production cost model capable of reporting hourly dispatch.

The Inflation Reduction Act (IRA) is not accounted for within the 2021 Standard Scenarios. We do not expect that this omission will significantly impact our overall conclusions since the supply-side decarbonization scenarios we consider are, on average, more demanding than what is likely to be realized through the IRA and other existing policies alone.

[23] Load growth assumptions in Cambium are based on the AEO 2021 reference scenario for electricity demand growth rate. Electricity generation technology costs are based on the 2021 Annual Technology Baseline moderate projections.

Because Cambium optimizes for a minimum cost solution for the electricity system, there will be no difference between short-run and long-run solutions. Derivative attributes of these solutions (e.g., emissions, fuel mix) would differ, however, which is one reason we choose not to highlight those results given our methodology.

[24] Note that these marginal costs are not estimates of retail electric rates. They do not include utility cost recovery for distribution infrastructure, EE incentives, or administration.

Our analysis also estimated portfolio costs (the marginal cost of obtaining the required generation through operations or purchase, to meet existing state-level renewable portfolio standards and clean energy standards). These costs are not presented in our results as they were minimal throughout all scenarios.

We chose to perform our analysis with the two Standard Scenarios within Cambium that best match our constraint of a high renewable energy future: one in which the U.S. power sector emissions are constrained to decrease linearly 95% below 2005 levels by 2050 (MidCase 95x2050), and a more ambitious future in which emissions decrease 95% by 2035 (MidCase 95x2035) and 100% by 2050.

In order to align with the grid regions reported in Scout, we use Cambium data aggregated at the Generation and Emission Assessment (GEA) level, as shown in figure 11. To understand how the building stock, grid mix, and climate of a region impact our results, we analyze five separate Cambium grid regions:

- ERCT = Texas
- CAMX = California
- NWPP = Washington, Oregon, Idaho, Montana, Nevada, Utah, Wyoming
- RFCW = Illinois, Indiana, Ohio, West Virginia
- SRSO = Alabama, Georgia

The marginal costs of energy and capacity in each region (as reported by Cambium) are fairly similar between the 95x2050 and 95x2035 scenarios in both 2030 and 2050. However, the energy (figure 7) and capacity (figure 8) costs have different trajectories in the intervening years. For both energy and capacity, costs stay relatively low in the 2030s, then begin ramping upward around 2040 in the 95x2050 scenario. In contrast, energy and capacity costs increase gradually starting around 2030 and 2024, respectively, before plateauing during the 2040s under the 95x2035 scenario. This suggests that energy efficiency is likely to be more valuable in avoiding total electricity system costs under a more rapid supply-side decarbonization scenario.

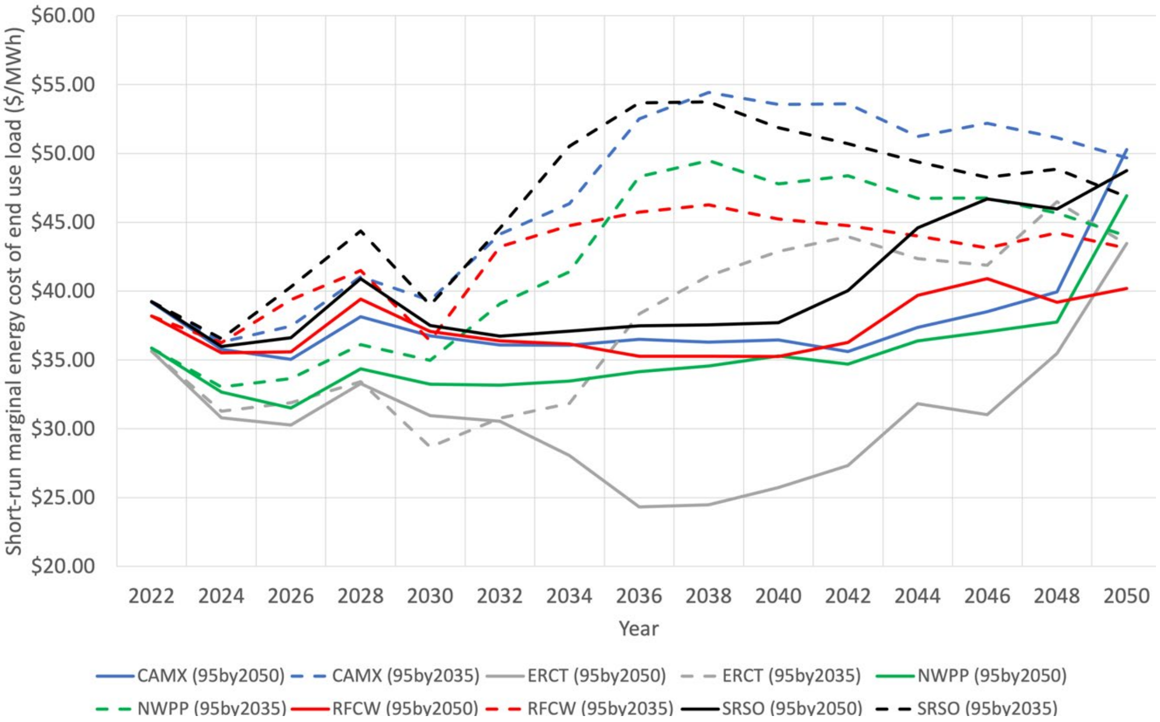

Figure 7. Average short-run cost of providing the energy needed to satisfy a marginal increase in load. Values in this chart are population-weighted averages of Cambium state-level data.

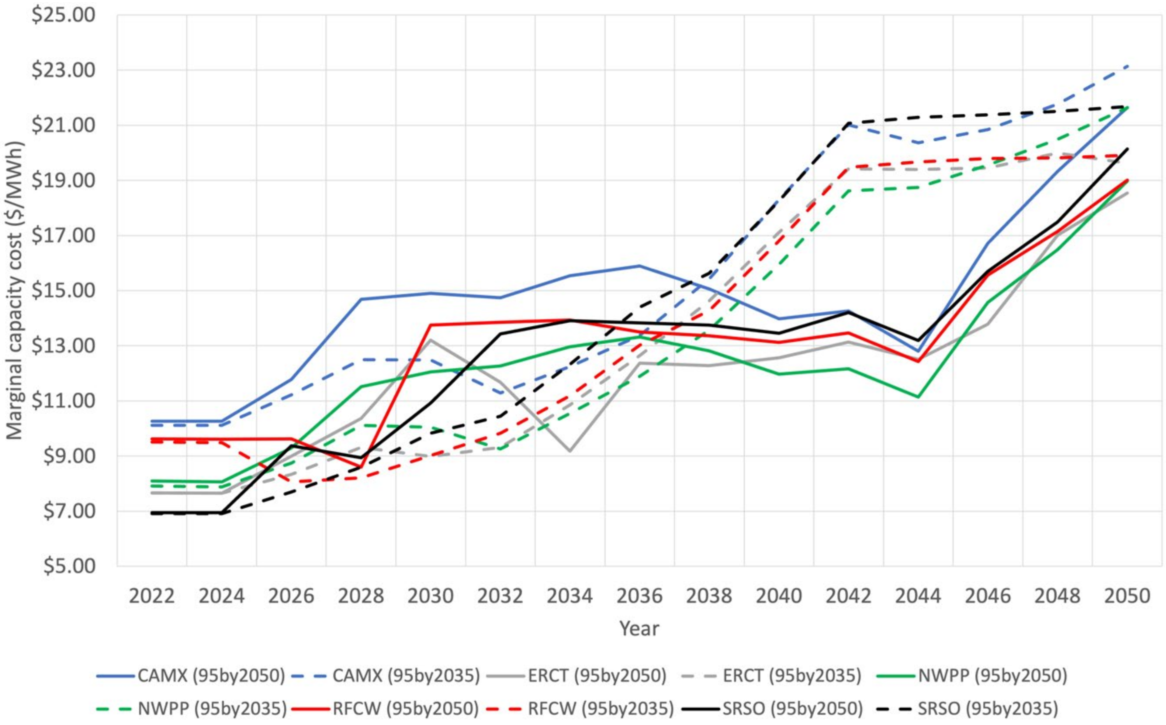

Figure 8. Average long-run cost of additional capital investment needed to maintain a target planning reserve margin when demand is increased. Values in this chart are population-weighted averages of Cambium state-level data.

RESULTS

In this section we present the results of the quantitative analysis described in the section "Demand-Side Measures within the Standard Scenarios." We begin by reporting the annual marginal avoided costs achieved by each of our EE measures/packages in 2030 and 2050. Then, we more deeply explore the transition to 2050 by delving into the regional growth in avoided costs that EE can provide in the 2030s and 2040s. Next, we shift to a peak day perspective and illustrate how EE will impact the grid on peak demand days in a high renewable energy future, including what generation may be called upon to meet load during those days. Interpretation of these results are reserved for the "Discussion" section that follows.

Figure 9 and figure 10 report the annual marginal avoided costs achieved by each energy efficiency measure or package under the 95x2050 scenario in the Midwest and Texas regions, respectively. Results are provided for both 2030 and 2050. Results for the remaining three regions and for the 95x2035 scenario are located in "Appendix B–Additional Results." The reported savings for each measure/package reflect the avoided costs if that measure/package was implemented in isolation.[25] With the exception of the "combined" measures presented, the savings from the measures below are independent of each other.

To place these energy savings and avoided costs into context, in figure 11 we show how much energy can be saved regionally in 2030 and 2050 if all efficiency measures in our analysis are pursued. A comparison of avoided costs broken out by residential and commercial sectors is provided in figure 12 for the 95x2050 scenario (results for 95x2035 are in "Appendix B–Additional Results"). We caution that the results in figure 12 are approximations designed to facilitate comparisons between sectors, regions, and years. The absolute savings reported on the horizontal axis are the sum of marginal avoided costs (in dollars) and do not account for changes in marginal avoided costs ($/MWh) that would result from substantial load reductions.

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[25] If all these EE measures were implemented simultaneously, the substantial drop in demand would alter the hourly avoided system costs ($/MWh), thereby impacting the reported annual totals.

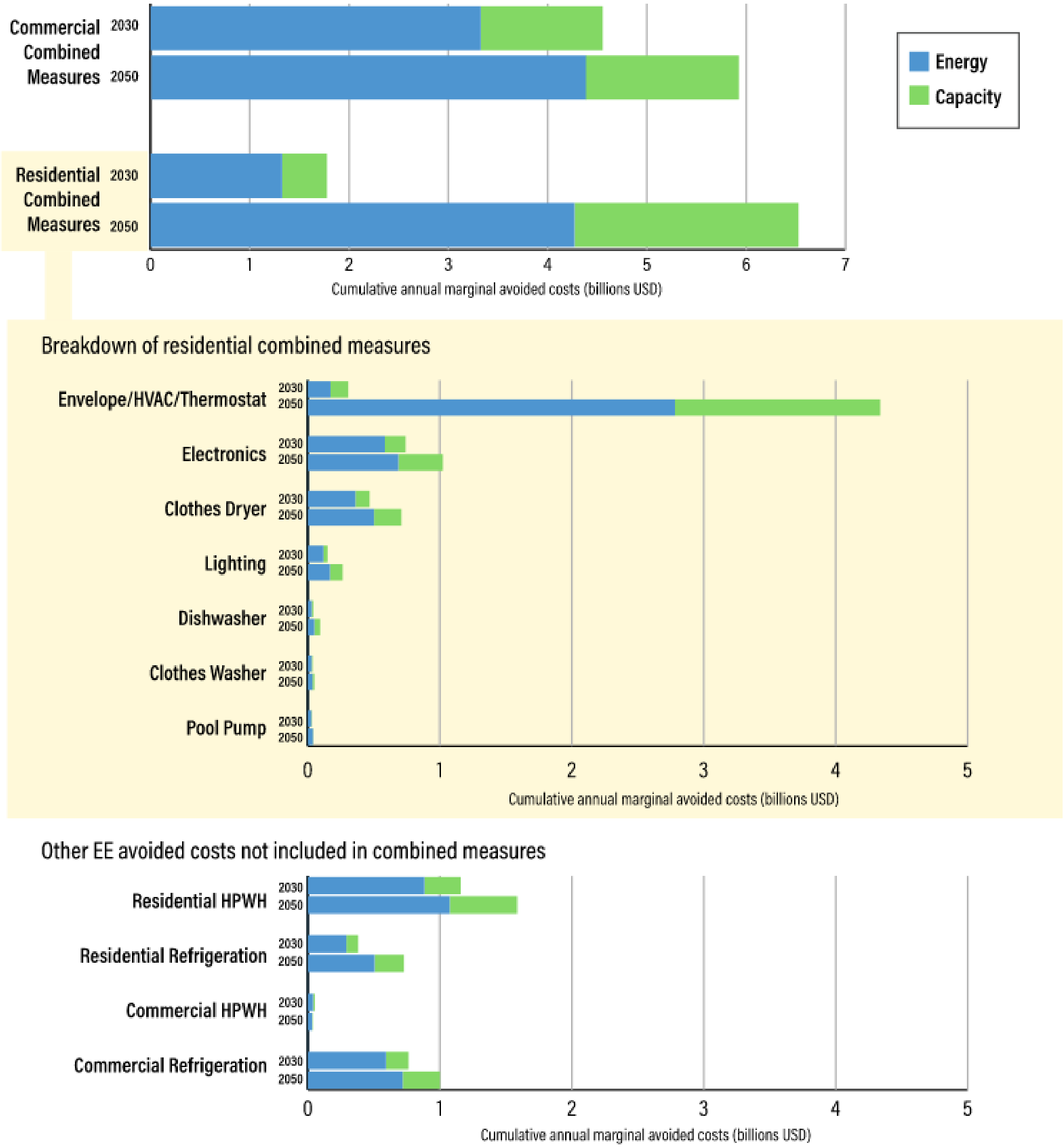


Figure 9. Annual marginal avoided costs in the Midwest (RFCW) in the MidCase 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. The Residential Combined Measures are aggregated to in order to be comparable with the preconstructed Commercial Combined Measures.

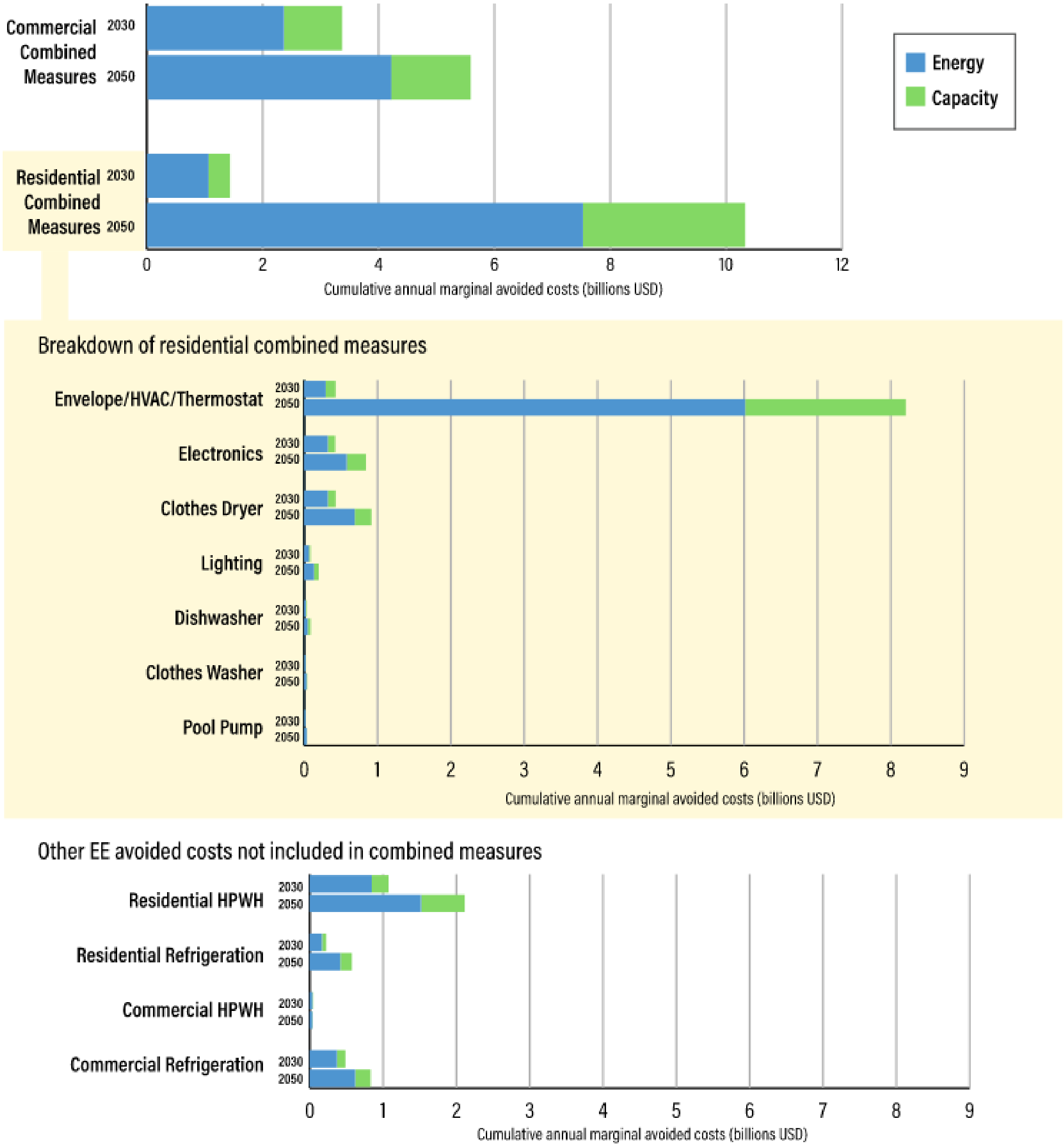


Figure 10. Annual marginal avoided costs in Texas (ERCT) in the MidCase 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. The Residential Combined Measures are aggregated in order to be comparable with the preconstructed Commercial Combined Measures.

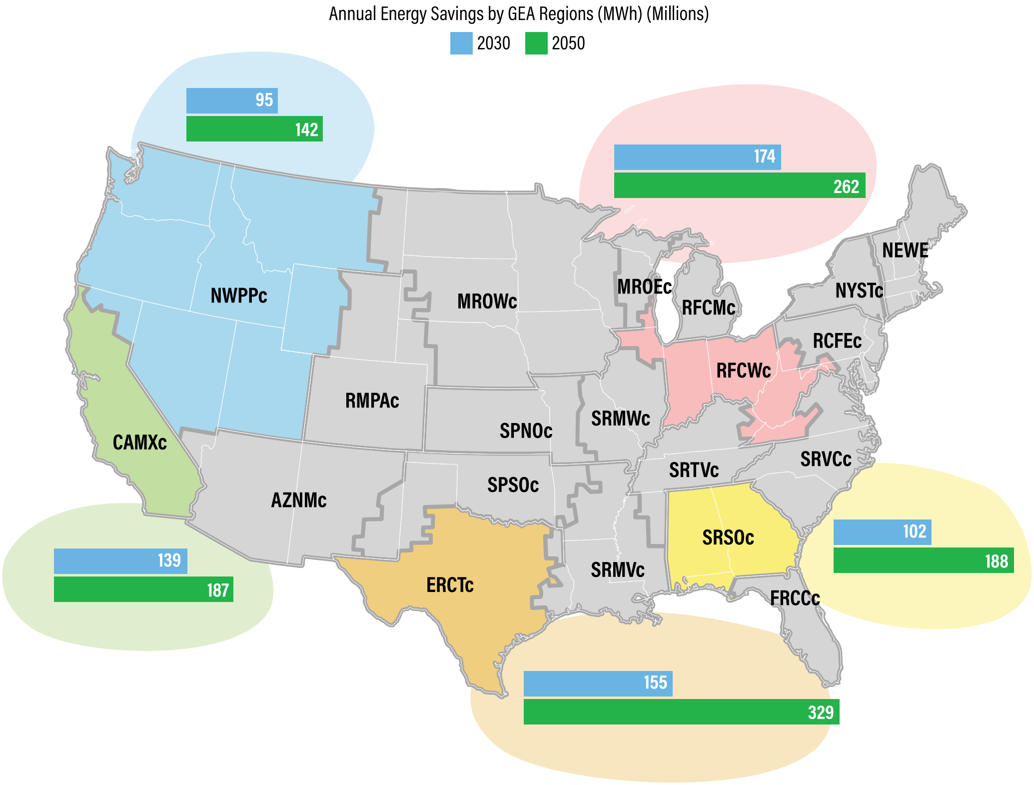


Figure 11. Energy saved by our aggregated residential and commercial energy efficiency measures and packages in each of the five GEA regions considered in this analysis. Savings are presented for 2030 (blue) and 2050 (green).

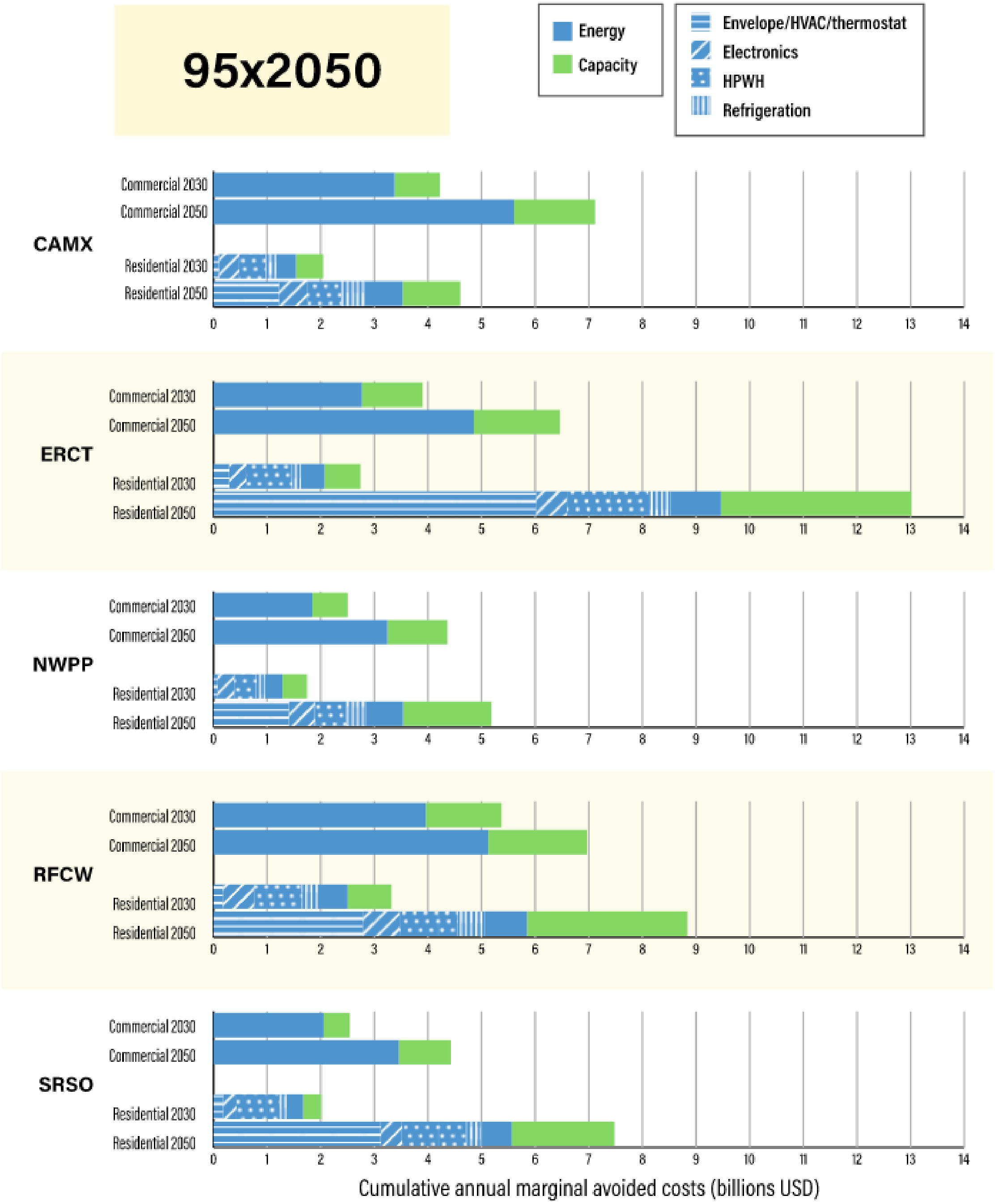


Figure 12. Sum of annual marginal avoided electricity system costs achieved by our set of energy efficiency measures and packages in the 95x2050 renewable energy scenario. Avoided costs are separated by residential and commercial sector. Four of the largest avoided cost drivers (i.e., envelope/HVAC/thermostat, electronics, HPWH, and refrigeration) are broken out for the residential sector. Because of the interactive effects of commercial EE measures, a similar breakdown was not possible for the commercial sector.

The results in figure 12 indicate that avoided costs achieved through energy efficiency increase between 2030 and 2050. The combined effect of technology improvement and stock turnover leads to energy savings that increase by mid-century for almost all measures in table 3. The magnitudes of these increases are shown in table 4.

Table 4. Increase in annual energy savings (GWh) for each of our energy efficiency measures/packages between 2030 and 2050

Measure	CAMX	ERCT	NWPP	RFCW	SRSO
Residential Envelope/HVAC/Thermostat	19,714 (750.0%)	119,246 (1309.9%)	23,448 (1010.9%)	50,682 (1204.0%)	53,047 (1132.9%)
Commercial Combined Measures	19,634 (24.2%)	22,887 (30.6%)	12,848 (27.2%)	18,921 (21.3%)	16,242 (24.2%)
Residential HPWH	–377 (–2.7%)	11,923 (44.2%)	591 (4.7%)	4,573 (19.1%)	5,652 (25.9%)
Residential Refrigerator	3,389 (60.6%)	4,514 (80.7%)	3,334 (66.4%)	4,867 (60.9%)	2,569 (74.5%)
Residential Clothes Dryer	2,895 (43.1%)	6,717 (64.4%)	3,326 (49.3%)	3,372 (34.2%)	3,069 (49.7%)
Commercial Refrigeration	625 (4.3%)	2,454 (19.5%)	809 (9.9%)	1,980 (12.1%)	1,982 (21.3%)
Residential Electronics	669 (6.6%)	3,535 (33.6%)	1,160 (12.8%)	1,594 (10.2%)	1,592 (24.1%)
Residential Lighting	807 (40.9%)	1,220 (60.6%)	812 (44.8%)	1,245 (40.8%)	695 (51.4%)
Residential Dishwasher	542 (87.3%)	550 (94.5%)	505 (89.3%)	513 (71.9%)	261 (80.5%)
Residential Pool Pump	205 (39.6%)	384 (68.7%)	225 (47.1%)	346 (43.4%)	275 (60.0%)
Residential Clothes Washer	122 (24.9%)	247 (45.3%)	140 (31.2%)	169 (21.5%)	121 (35.6%)
Commercial HPWH	–279 (–38.3%)	–150 (–14.2%)	–115 (–28.9%)	–199 (–18.4%)	–19 (–2.4%)

Values in parenthesis reflect the percentage change in annual energy saved over that span. Negative values indicate that a measure saves less energy relative to its baseline in 2050 than in 2030. HPWH = heat pump water heater.

In table 5, we sum the annual marginal avoided costs in each year to approximate the extent of that growth. Those avoided costs are disaggregated into their residential and commercial contributions in table 6.

Table 5. Sum of marginal electricity system costs (in billions of dollars) avoided in 2030 and 2050 by energy efficiency measures/packages in table 3 for the 95x2050 scenario

Region	2030	2050	% Change
CAMX	$6.297	$11.723	+86%
ERCT	$6.643	$19.474	+193%
NWPP	$4.255	$9.542	+124%
RFCW	$8.692	$15.809	+82%
SRSO	$4.559	$11.913	+161%

Table 6. Same information as in table 5, but broken out by the residential contribution (left) and the commercial contribution (right)

Region	2030	2050	% Change
CAMX	$2.055	$4.609	+124%
ERCT	$2.740	$13.014	+375%
NWPP	$1.749	$5.180	+196%
RFCW	$3.320	$8.843	+166%
SRSO	$2.013	$7.483	+272%

Region	2030	2050	% Change
CAMX	$4.242	$7.115	+68%
ERCT	$3.903	$6.460	+66%
NWPP	$2.506	$4.362	+74%
RFCW	$5.372	$6.966	+30%
SRSO	$2.546	$4.430	+74%

The hourly resolution provided by the Scout and Cambium data also enable us to explore the impact these energy efficiency measures will have on representative peak days in the future. We present samples of these peak days in figure 13 and figure 14 to provide insight into how the energy efficiency measures that deliver the greatest avoided energy costs through the course of a year also provide (mostly) avoided capacity benefits during days with the highest hourly avoided costs of the year.

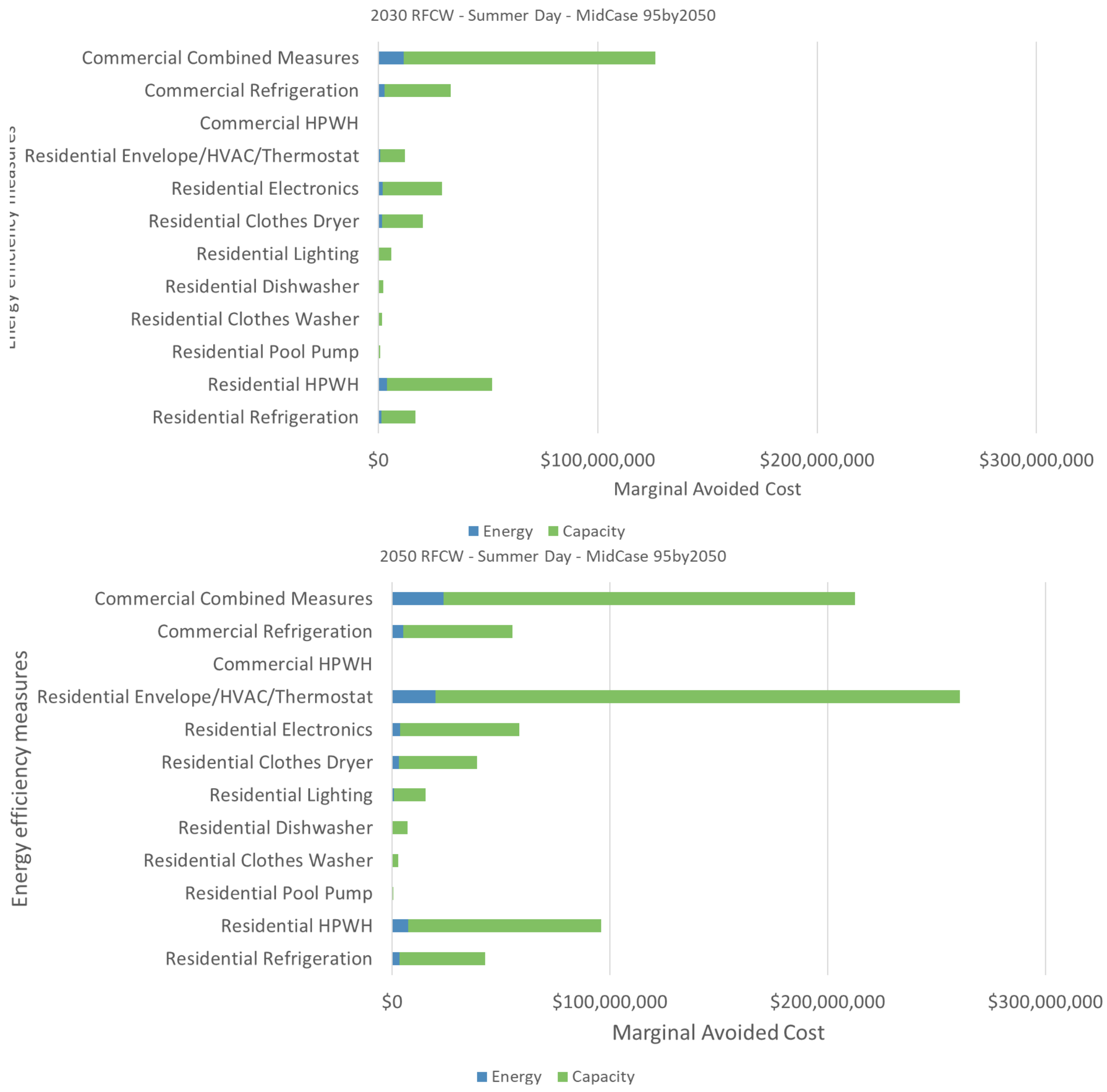
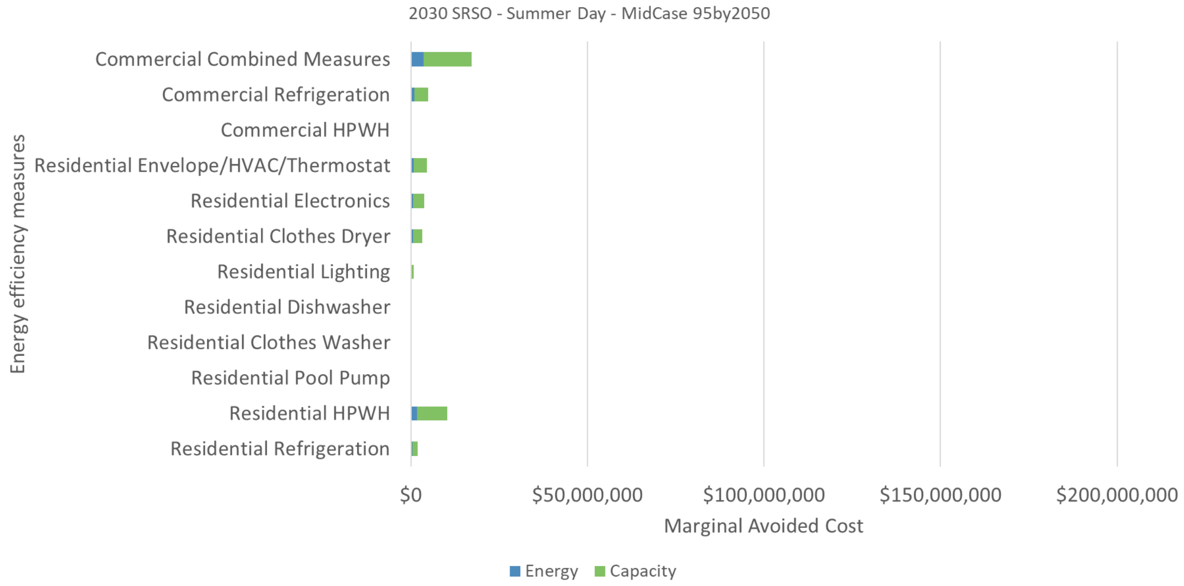


Figure 13. Summer peak day marginal avoided costs in the Midwest (RFCW) in the 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs in both figures are drawn from July 7 within Cambium, while energy savings are drawn from July 22 within Scout (see Appendix A for additional details on selecting peak days).



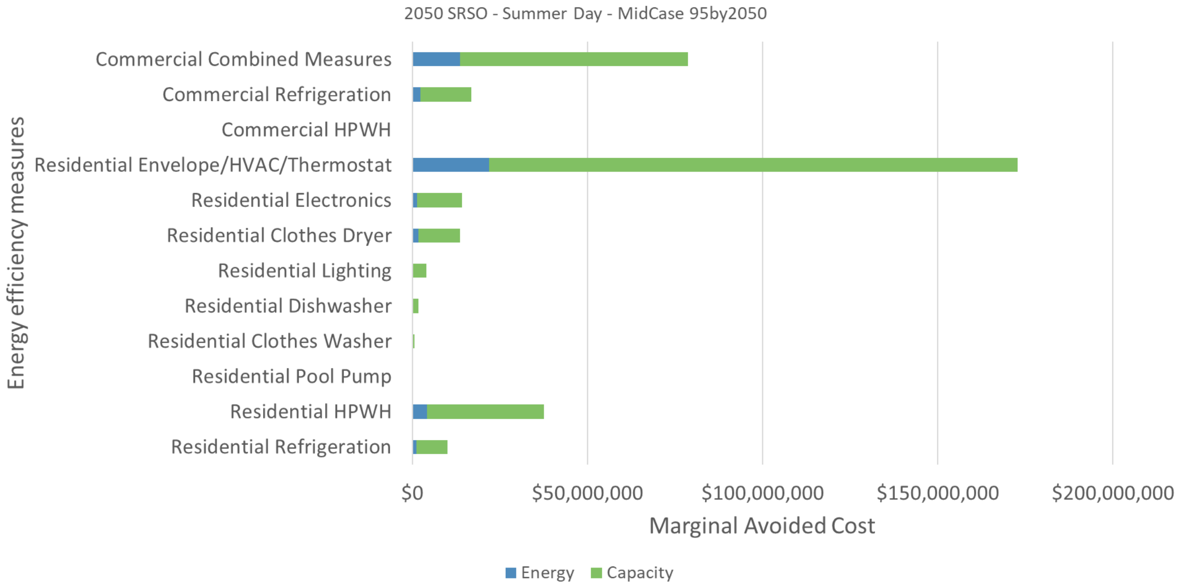


Figure 14. Summer peak day marginal avoided costs in the Southeast (SRSO) in the 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs are drawn from June 29 (2030) and July 1 (2050) within Cambium, while energy savings are drawn from July 9 (2030) and July 8 (2050) within Scout.

Additional peak day results are provided in "Appendix B–Additional Results." These include peak day load savings shapes and tables that report which measures/packages deliver the largest avoided energy costs by year and renewable energy scenario.

In addition to exploring *peak load* in detail, we also chose to investigate the role of energy efficiency during *peak net load* days. Net load equals the difference between total demand and the amount of that demand that is met by renewable energy. An alternative way of thinking about net load is the demand that must be met with dispatchable (i.e., non-variable) generation. In a high renewable energy future, keeping net load low reduces both GHG emissions and the costs associated with maintaining and operating fossil-based generation, including plants with low load factors.

We define a year's *peak net load day* as the day within the Cambium dataset that contains the highest reported hourly net load at the busbar (see table A3).[26] For every region, the hour with the highest net load during a peak net load day occurred in summer between 7 pm and 10 pm. We then generated the overall load profile and energy savings load shapes for each of those peak net load days from Scout data in the same manner as for conventional peak days.

In order to consider the impact that energy efficiency measures might have on supply-side resources, we visualized the load reduction from efficiency alongside the projected electric generation mix during peak net load days. Figure 15 and figure 16 illustrate how our energy efficiency measures perform. We assumed renewable energy would be utilized first, followed by nuclear, with fossil-based resources dispatched last. The peak reductions realized by energy efficiency are shared in table 7. Additional details on this methodology are presented in "Appendix A" and additional peak net load day profiles are in "Appendix B–Additional Results."

Table 7. Peak load and peak net load reductions achieved by our full set of EE measures/packages during the indicated years' peak net load day

GEA region	Peak load reduction 2030	Peak load reduction 2050	Peak net load reduction 2030 (95x2050)	Peak net load reduction 2050 (95x2050)	Peak net load reduction 2030 (95x2035)	Peak net load reduction 2050 (95x2035)
CAMX	33.1%	39.2%	46.1%	69.3%	44.9%	59.8%
ERCT	25.7%	51.5%	33.8%	86.2%	35.7%	81.8%
NWPP	27.5%	48.8%	38.9%	76.7%	39.2%	77.3%
RFCW	24.5%	32.8%	31.2%	39.2%	24.7%	39.3%
SRSO	23.7%	46.7%	34.7%	66.2%	39.1%	62.3%

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[26] Within Cambium, this value is stored in the field *net_load_busbar*. This value equals the difference between the quantity of load consumed at the busbar level to meet the demand for electricity consumed at the point of end use within a region and the total generation from all variable generators within a region (i.e., solar photovoltaic, concentrating solar power, and wind).

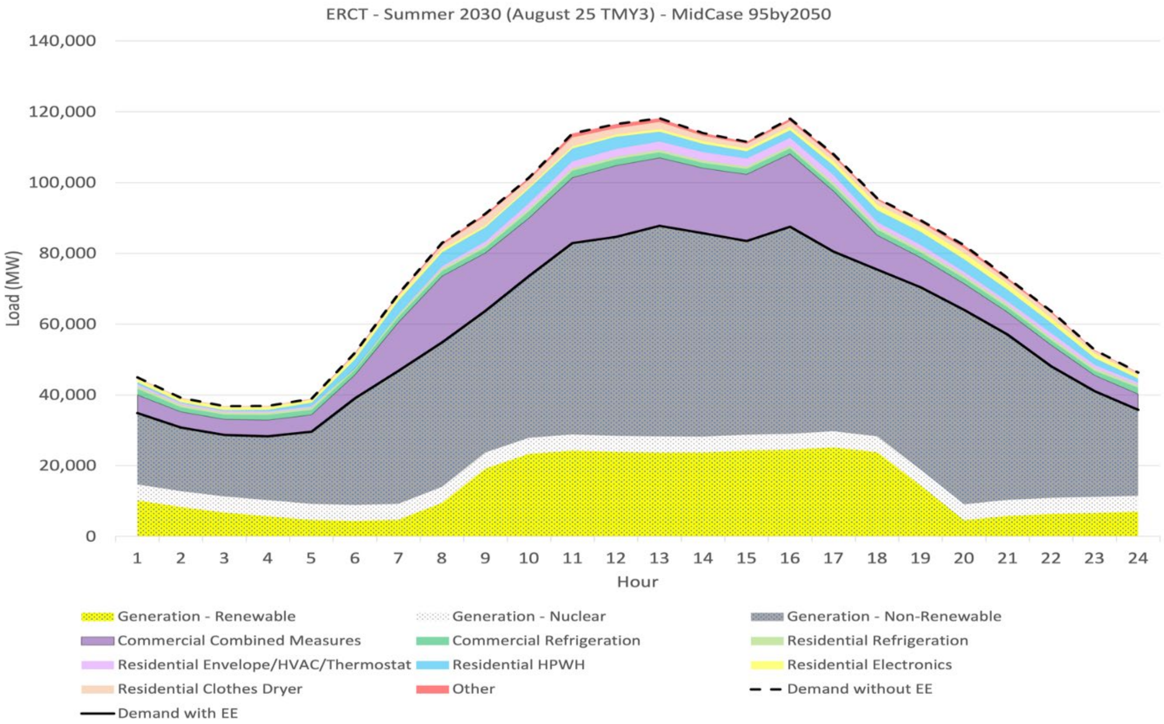

Figure 15. Load reduction potential of energy efficiency measures during a peak net load day (August 31) in Texas (ERCT) in 2030 under the 95x2050 scenario

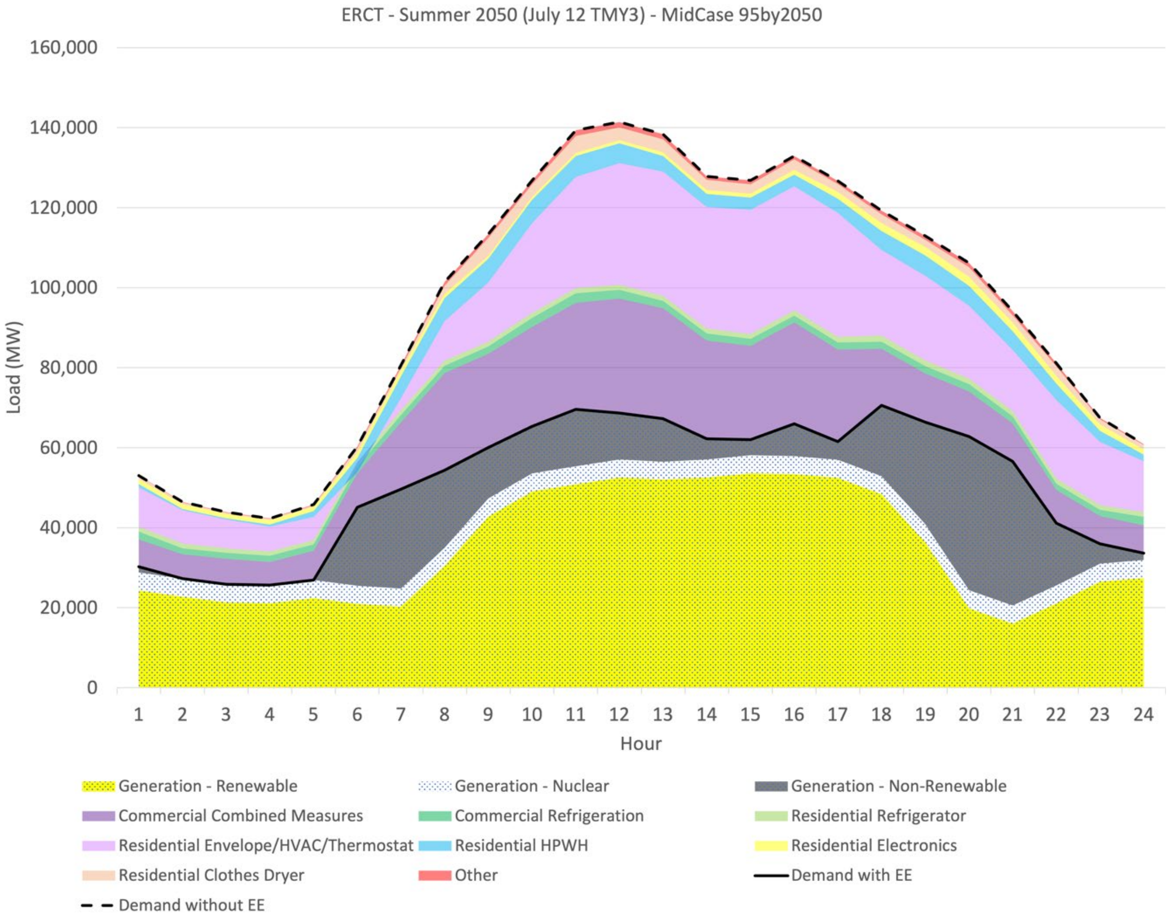

Figure 16. Load reduction potential of energy efficiency measures during a peak net load day (June 26) in Texas (ERCT) in 2050 under the 95x2050 scenario

Discussion

This section will impact the central findings from our literature review and quantitative measure-level analysis. Many common themes emerged, such as the large potential benefits of thermal space conditioning measures, but there were also regional differences. We begin in the section "How Energy Efficiency Enables a Low-Cost Renewable Energy Future" by summarizing the impacts at a high level. We also provide recommendations for grid planners. Next, in the section "Energy Efficiency Measure Recommendations" we interpret the results of our quantitative analysis, identifying which energy efficiency measures will be most valuable in reducing future system costs before offering recommendations for energy efficiency program designers. We conclude in the section "Avoided Cost Trends" by taking a closer look at why avoided costs go up through 2050 even with high amounts of renewable energy on the grid.

HOW ENERGY EFFICIENCY ENABLES A LOW-COST RENEWABLE ENERGY FUTURE

In this report we have identified a number of barriers and challenges to a high renewable energy future that energy efficiency helps alleviate. Though not included in our modeled results, these barriers include land acquisition for solar and wind generation, critical materials mining, supply chain issues, transmission siting, distribution system upgrades, long and increasingly expensive interconnection queues, rising energy costs as the system approaches 100% renewable energy, and reliance on expensive and unproven technologies.

Our results show that energy efficiency measures alone can deliver hundreds of billions of dollars in avoided electricity system cost benefits annually by 2050, with savings increasing as the electric grid becomes increasingly renewable. Energy efficiency can enable a highly renewable future not only by reducing the overall electric demand that must be met but also by helping to displace the need for fossil-powered marginal generators (thereby lowering marginal emissions). This is in addition to the ample customer and societal benefits of energy efficiency (e.g., reduced bills, improved health impacts, and home comfort).

On a levelized cost of energy basis, renewable energy is now competitive with energy efficiency. Yet as renewable energy installations proliferate, there will be diminishing returns on incremental additions of those resources. Meeting the last few percentage points of energy demand in a high renewable energy future will become increasingly expensive, as currently projected solutions like storage, carbon capture, and decarbonized fuels are either expensive, unproven, or both.

While eschewing energy efficiency for renewable energy might minimize system costs in the near term, it does not necessarily ensure that we are adequately investing in reducing loads for a long-term transition rife with costly technical and political challenges and uncertainty. Additionally, clear and proven transmission and distribution system benefits from pursuing energy efficiency exist even when the near-term costs are similar to renewable energy. As such, it is imperative that system planners consider adjusting their avoided cost calculations to incorporate the long-run benefits from energy efficiency, such as delayed costs and meeting climate goals on time. Overreliance on the current levelized cost of energy might result in underinvesting in energy efficiency and missing the opportunity to reduce overall system costs and maximize public interest benefits in the long term. Existing cost-effectiveness tests do not necessarily capture the benefits that energy efficiency provides by enabling the transition to a predominantly renewable grid.

Among the pathway studies reviewed for this report, those that rigorously considered energy efficiency within their modeling found that it was a critical component of meeting climate goals. Yet existing approaches to modeling renewable energy pathways typically treat energy efficiency as an exogenous resource, that is, as an *input to* rather than an *output from* the model. When EE is parameterized a priori, it cannot dynamically compete against other energy resources, limiting its potential to emerge as a preferred resource during a utility procurement process. Vibrant Clean Energy, one of the few companies with an energy system modeling framework capable of analyzing distributed energy resources endogenously, finds that including DERs (including energy efficiency) as an endogenous factor in system modeling could generate system-wide savings between $301 billion and $473 billion by 2050 and allow more efficient deployment of clean utility-scale variable generation (Clack et al. 2020).

ENERGY EFFICIENCY MEASURE RECOMMENDATIONS

Commercial Measures

The Commercial Combined Measures deliver approximately half of annual avoided electricity system costs in 2030 across regions and renewable energy scenarios we considered in this analysis (see table 8). This is partly by virtue of the large number of measures included in this package (which are difficult to analyze separately due to their interactive effects).

Table 8. Percentage of avoided total electricity system costs attributable to commercial combined energy efficiency measures (i.e., envelope, HVAC, lighting, and plug loads)

Region	2030 (95x2050)	2050 (95x2050)	2030 (95x2035)	2050 (95x2035)
CAMX	56.2%	52.2%	56.2%	52.0%
ERCT	50.7%	28.7%	50.3%	28.8%
NWPP	50.4%	39.8%	50.2%	39.5%
RFCW	52.4%	37.5%	50.2%	37.6%
SRSO	46.2%	31.2%	45.3%	31.2%

The renewable energy scenario is indicated within parentheses.

These results indicate that commercial energy efficiency programs will remain an area of opportunity across the country. As a percentage of total avoided costs, the commercial combined measures offer the most benefit through 2030. However, they only deliver 35–73% of the avoided costs of residential measures by 2050 under both renewable energy scenarios, except in California where commercial combined measures constitute about 130% of the avoided costs of residential measures in 2050.

This trend is partly explained by the expected adoption rates of new building technologies. While our analysis assumes a similar HVAC replacement rate in existing residential and commercial buildings, over the next decade new commercial buildings are projected to be built at approximately twice the rate (>2% per year) of new residential buildings (1% per year) (EIA 2022c). This introduces more near-term opportunities for commercial measures than residential. In the two decades that follow, this trend reverses. The residential electric HVAC market is projected to grow 7%, while the commercial electric HVAC market is projected to contract 5%, reflecting the influence of more efficient new construction in the commercial baseline. Taken together, these trends help explain why we should expect to see more near-term value from commercial HVAC/envelope measures through 2030, but longer-term value from residential HVAC/envelope measures between 2030 and 2050.

The commercial combined measures in this analysis do not include building controls or heating distribution measures, which may provide additional savings.

Policy Implications:
Efficiency program designers should ensure that they have robust offerings for new commercial buildings over the next decade. Existing buildings should also be targeted for envelope and HVAC upgrades. The potential energy savings and avoided system costs are large, but utilities will need to take advantage of limited opportunities to intervene at times when building operators are amenable to equipment replacement. Electrification measures may especially require advance planning for equipment replacement, as replacing fossil systems at failure may be complex. Educational materials should be provided to customers well in advance of equipment end of life to prime them to make the transition to more efficient heating and cooling technologies when it is time for replacement. This is especially true in California, where commercial combined measures show the greatest potential savings among any region, year, or renewable energy scenario we studied—and so should be a priority for California energy efficiency program designers in the near and longer term.

Residential Thermal Space Conditioning

Residential thermal space conditioning measures (HVAC improvements paired with envelope and thermostat upgrades) offer modest avoided cost potential by 2030 but grow to represent the greatest residential savings opportunity in 2050. This trajectory has much to do with the fact that HVAC equipment is only replaced at the end of its useful life, or approximately once every 15–25 years.[27] Our analysis assumes that all space conditioning measures, including thermostat measures, are installed simultaneously. However, this means we do not capture savings from measures that could be installed during the building or HVAC system lifecycle, such as building controls (including lighting) and envelope retrofits (including air sealing, window inserts, low-E window film, and exterior insulation).

The future value of thermal space conditioning measures is computed relative to an assumed regional baseline and depends upon a variety of factors. These include a region's climate, existing building energy codes (i.e., more stringent existing energy codes reduce the potential savings), the quality of the existing building stock (e.g., draftier existing buildings have more potential savings), and the amount of new construction planned in each region. California's relatively mild climate, high existing baseline efficiency standards, and more stringent building energy codes combine to limit the savings potential from these measures

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[27] This trajectory may be accelerated slightly if home electrification rebates offered through the Inflation Reduction Act of 2022 are deployed effectively.

in 2050. In contrast, savings opportunities are much larger in Texas and the Southeast in 2050 as a result of those regions' higher summer temperatures, high existing share of electric heating (which makes more homes eligible for our modeled energy efficiency packages), and larger and more poorly insulated homes.

Policy Implications:
Thermal space conditioning measures should be the priority for energy efficiency program designers in all regions studied. Because the level of savings is constrained by stock turnover rates and will take decades to reach its full potential, these actions should begin immediately and proceed continuously. Upgrading to high-performance air source heat pumps is the clear choice in regions like Texas, but will also reduce lifecycle costs for customers across much of the country (Nadel and Fadali 2022). However, program designers should be mindful that lower-income customers will need a higher share of installation cost covered for more capital-intensive measures like heat pumps. Additionally, low-income customers often have structural impediments to installing these measures (e.g., mold, roof damage, water infiltration) that need to be remediated before envelope measures can be installed. They should attempt to braid ratepayer funds with other sources of state and federal support (e.g., Low Income Home Energy Assistance Program (LIHEAP), Medicaid) to ensure that system costs are minimized and that low-income customers can enjoy the benefits of ratepayer-funded programs (Hayes and Gerbode 2020).

Utilities should incentivize substituting central air-conditioning systems with high-efficiency air source heat pumps at the time of replacement. The heat pumps will not only provide equal or better cooling during summer months but will offer efficient electric heating capabilities during winter months, which, if they replace inefficient electric heating systems, will be a critical efficiency resource when regions gradually begin to see winter peaks on their electric grid. Though this substitution is not captured in our analysis, many leading states have discontinued incentives for central air-conditioning efficiency upgrades when an air source heat pump may be a better fit.

Heat Pump Water Heaters

Among residential measures, switching from less efficient electric water heaters to heat pump water heaters consistently ranks second behind only thermal space conditioning measures in terms of avoided electricity system costs. Residential heat pump water heaters substantially reduce electric system costs through mid-century. Moreover, most water heaters have effective useful lifetimes that are short enough for stock turnover to play a positive role by 2030.

Commercial heat pump water heaters do not show the same potential as their residential counterparts and delivered among the lowest savings of the efficiency measures analyzed. The AEO projects a very small baseline energy consumption level for this end use, which results in comparatively smaller savings over time. Moreover, AEO forecasts that a 12% decrease in electric commercial water heating service demand will combine with improvements in baseline water heating technology to produce a decrease in commercial water heating energy demand of about 19% between 2030 and 2050.[28] As a result, the energy savings attributable to commercial electric heat pump water heating efficiency measures (beyond baseline efficiency assumptions) are lower in 2050 than in 2030.[29]

Policy Implications:
Efficiency programs interested in avoiding electricity system costs through energy efficiency should favor residential heat pump water heater measures. Despite the projected growth in gas-powered water heating in some sectors, we recommend focusing efficiency program dollars on water heating electrification. Such measures will make heat pump water heaters more cost competitive with gas water heaters, reduce total energy consumption, and allow utilities to claim greater GHG reductions from their programs.

Other Measures

Energy efficiency measures related to residential refrigeration, electronics, and clothes dryers have moderate potential to reduce electric system costs in 2030. These measures rise in relative importance to other measures through 2050. Residential electronics deliver relatively robust savings in 2050. Residential electronics represent a wide range of products, for which our efficiency measures assume a roughly 50% drop in plug load demand over this period. As discussed below, electronics are one of the more complex areas for utility intervention—these savings will likely be achieved largely through appliance standards and market evolution.

Among the energy efficiency measures we studied, commercial electric heat pump water heaters, residential dishwashers, residential pool pumps, residential clothes washers, and residential lighting have the lowest potential to reduce electric system costs through mid-century. Residential dishwashers, pool pumps, and clothes washers draw little power relative to many other building loads, which mitigates the potential savings from energy efficiency measures applied to these end-uses. Residential lighting efficiency measures largely involve replacing inefficient incandescent and less efficient compact fluorescent bulbs with LEDs. However, many of these savings have already been claimed by the residential sector and the residential lighting market has been transformed, such that over three-quarters of current residential lighting sales are LEDs (NEMA 2022). Additionally, new federal lighting standards will likely increase the baseline lighting efficiency and reduce the potential savings from future programs.

Policy Implications:

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[28] Savings are lower in California in 2050 for residential heat pump water heaters than 2030 for similar reasons. AEO's Pacific Census Division water heater forecast projects the baseline stock of electric water heaters to decrease by about 10% between 2030 and 2050, while the gas water heater stock increases by about 20%.

[29] Note that these are the only measures/packages in our modeling that exhibit lower savings in 2050 than 2030.

Energy efficiency program designers should continue to support all cost-effective energy efficiency, even if the energy savings and avoided costs are more modest. However, in order to maximize the benefits in a transitioning grid, designers should be strategic to maximize long-term avoided costs. For example, measures with modest savings could be targeted as part of a larger package of efficiency upgrades. Administrators could consider scaling up incentives if measures such as pool pumps, consumer electronics, dishwashers, and clothes washers are upgraded simultaneously.

Residential electronics is a challenging area for utility intervention because it encompasses a wide array of products subject to various market forces. Some more efficient electronics might be adopted organically into the market (e.g., the move away from desktop computers and cable boxes), while improved device efficiencies for others are best realized through efficiency standards including state and/or federal minimum standards for external and internal power supplies, battery charging efficiency, standby power usage, and improved standards and labeling for the largest consumer electronics. Utility programs can offer rebates for larger consumer electronics through the ENERGY STAR Retail Products platform, provide incentives for advanced power strips or outlets capable of achieving standby and off-mode savings, or promote home energy management systems.

These residential measures will require specific attention to renters and low-income customers. These residents tend to have older, less efficient equipment in their homes, but also tend to have less equipment overall (e.g., pool pumps, dishwashers, clothes washers are not ubiquitous). Program administrators will need to carefully design incentives that address various types of residents to maximize savings from home appliances.

AVOIDED COST TRENDS

Avoided Energy Costs

Despite the increasing saturation of renewable sources with low or zero marginal energy costs, the energy efficiency measures we examined predominantly displaced energy costs. In the 95x2050 scenario, between 73% (Texas) and 82% (Southeast) of annual electric system costs avoided by energy efficiency measures in 2030 are energy costs, with the bulk of the remainder being capacity costs. The makeup of avoided costs is similar in 2050, though energy costs represent a slightly smaller share of total avoided costs, ranging from 69% to 78%. These results are similar in both renewable energy scenarios.

The modeling reflected in the Cambium dataset (from which we draw avoided costs) includes a constraint that requires 95% of electricity to be decarbonized by either 2035 or 2050. Although the marginal price for renewable energy hovers around zero, the fossil and carbon capture resources needed to provide the final 5% of electricity become much more expensive in a high renewable energy future. This leads to a net *increase* in total electricity system costs and helps explain why energy efficiency will continue to be so valuable going forward.

To understand this more intuitively, consider that the Annual Energy Outlook, which projects renewable energy capacity in the absence of new policy, projects less renewable energy will be deployed through 2050 than we included in our modeling. This implies that AEO's least-cost solution for balancing supply and demand in the absence of new policy (like the Inflation Reduction Act) involves more fossil-based resources like natural gas, and less renewable energy. Imposing a constraint (e.g., 95% renewable energy by 2050) on the least-cost optimization problem precludes certain grid topologies, including the one that would result from AEO's least-cost solution. The remaining decarbonized grid solutions wind up being more expensive, as do future avoided energy costs.

Because our analysis is limited to marginal costs, it is important to consider the long-term costs that are not quantified. Over the long run, energy efficiency will impact what generators get built. Lowering overall demand on the system through efficiency will lower not only the marginal fuels that are called on to meet demand on peak days but will also potentially reduce the need for future capacity, including renewable capacity.

Peak Day Analysis

Our analysis of days with the highest electric system costs showed that the rank ordering of the best performing energy efficiency measures remains mostly unchanged compared to annual results. In other words, the measures that are important on an annual basis (e.g., envelope, residential hot water heating) remain important on peak days, while the measures that do not show robust annual value (e.g., residential lighting, residential clothes washers) do not show that value during peak days either.

In contrast to the makeup of annual avoided costs (predominantly energy costs, as discussed in the previous section), between 77% and 93% of the avoided costs on peak days are from reduced capacity costs.[30] As discussed in the "Energy Efficiency's Role in Pathway Studies" section, installing sufficient capacity is one of the largest obstacles to getting to a highly renewable electric grid. Avoided peak day costs illuminate an essential role energy efficiency plays in enabling a highly renewable future: reducing (or avoiding) the need for additional generation, transmission, and distribution capacity on the days with the highest energy demands and doing so with resources that are reliable and durable. Moreover, as climate change contributes to more extreme temperatures and as buildings increasingly electrify, thermal space conditioning needs on peak days will grow. Under these circumstances, load reductions afforded by efficiency will play an essential role in managing peaks.

Figure 15 and figure 16 (as well as additional results in "Appendix B–Additional Results") indicate that peak day load reductions tend to displace fossil generation. On these highest demand days, energy efficiency has the potential to reduce peak load that would otherwise be met by fossil-based resources or load curtailment by 31–46% in 2030 and 39–86% in

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[30] This includes both winter and summer peaks.

2050. There are some scenarios (for example, early morning hours in California in 2050) where energy efficiency might displace renewable energy generation on peak days. However, this frees up those resources to recharge storage resources or satisfy time-shifted demand with the right programs and pricing in place.

Seasonal Trends

Though all measures in our analysis deliver year-round savings, seasonal savings vary by measure and region. From 2030 to 2050, the increase in electricity system avoided costs by virtue of residential thermal space conditioning measures is greater in summer than in winter. A comparison of representative peak days in summer and winter across all five regions show that summer avoided costs grow more quickly than winter avoided costs. The entire United States is projected to warm as a result of climate change. Consequently, summer cooling demand will increase, and winter heating demand will decrease, pushing more energy savings potential into the summer months.

However, it is important to remember that our model only assumes modest electrification (Annual Energy Outlook 2019 assumptions), and thus does not capture the expected growth in winter loads across the country that will result from the conversion from fossil-based heating to electric air source heat pumps. We refer the reader to other resources, including ACEEE's *Demand-Side Solutions to Winter Peaks and Constraints*, to better understand energy efficiency's role in mitigating winter demand increases due to electrification (Specian, Cohn, and York 2021).

Policy Implications:
Energy efficiency delivers savings year-round and is a reliable resource for passively reducing load on peak days. The projected future hourly generation mixes for the regions studied indicate that this reduction in load will generally displace fossil generation and, during peak hours, energy discharged from storage systems (e.g., pumped hydro, batteries). Instances when renewable generation is displaced provide an opportunity for additional energy storage or demand shifting.

Energy efficiency reduces load on peak days (when demand is highest) and will also do so on the *net peak days* when the amount of load met by fossil fueled resources is highest. When renewable generation capacity on the grid is low (i.e., most of the United States today), there is little difference between the two. In the future, however, peak load will be driven by periods of high demand and less renewable energy. The only energy efficiency measures within our modeling that differ appreciably based on seasonality are HVAC/envelope/thermostat and (to a lesser extent) water heating, which also happen to deliver peak load/peak potential savings when the exterior temperatures are most extreme (or coldest in the case of water heating).

Avoided Costs in 2030 Compared to 2050

The stark increase in avoided costs out to 2050 captures a range of benefits beyond most energy efficiency portfolio planning horizons. Across regions, annual electric system costs avoided by energy efficiency increase by a factor of approximately two to three between 2030 and 2050 (see table 5). The greatest growth was in the residential sector, where annual avoided costs increased 124–375%, compared to the commercial sector where avoided costs increased 30–74% in 2050 compared to 2030 (see table 6).

Avoided costs increase between 2030 and 2050 for a couple reasons. The first is that energy savings achieved by the energy efficiency measures that deliver the largest savings (i.e., commercial combined measures, residential envelope and HVAC, residential HPWH, commercial refrigeration, residential electronics, residential clothes dryer, and residential refrigeration) increase from 2030 to 2050, as more efficient technologies are adopted. The second is that total electric system costs also increase between 2030 and 2050 in both renewable energy scenarios, as described in the section "Avoided Energy Costs."

Our results indicate that the relative values of various energy efficiency measures to the electric system hold for both the 95x2050 and 95x2035 renewable energy scenarios. Overall, these annual avoided costs are fairly similar across the two renewable energy scenarios considered. None of the cumulative annual avoided costs vary by more than 20% between the scenarios, and the majority are less than 10%. This result is partially a coincidence resulting from the two years we have chosen to study in detail—2030 and 2050. In 2030, the decarbonization constraints are only just initializing within our models, while by 2050 the final decarbonization state has been reached for both scenarios.

However, energy efficiency measures are more valuable in the aggregate during the 95x2035 scenario than in the 95x2050 scenario. This is because in the former, avoided costs rise more quickly in the years between 2030 and 2050 and stay high longer. In contrast, in the 95x2050 scenario, avoided costs do not begin their inflection upward until about 2040, keeping avoided costs lower in the 2030s and early 2040s, and lowering the value provided by energy efficiency measures during that span (see figure 7 and figure 8). Despite the similarities between the two renewable scenarios, the results still provide a sense of how energy efficiency interacts with higher shares of renewable energy on the grid, since both scenarios have increasing shares of renewables between 2030 and 2050. They also capture the longer-term benefits of energy efficiency that are beyond the time horizon of the typical planning process.

Policy Implications:

Our analysis shows that the more quickly the grid decarbonizes, the more value energy efficiency can provide. However, our estimates of avoided costs are projected over longer periods and in more aggressive grid decarbonization scenarios than the typical energy efficiency planning process. Short-term energy costs and ready access to peaking resources can misleadingly make energy efficiency look less competitive in the near term compared to projecting out to the final years of decarbonization goals.

Conclusion

Our analysis shows that energy efficiency has a crucial role in decarbonizing the energy system and paving the way toward a high renewable energy future. Demand-side measures will reduce burdens on the power sector by reducing energy, generation, capacity, and transmission costs, with estimated savings in 2050 of $10–19 billion annually per grid region analyzed. Regionally, our analysis estimates measure-level avoided costs achievable by energy efficiency in high renewable future scenarios in order to inform regional planning strategies. Our findings build on existing decarbonization or high renewable energy pathway studies that evaluate the role of energy efficiency and almost universally find it to be among the key strategies for power sector decarbonization.

Individual energy efficiency measures and packages can avoid billions of dollars' worth of energy and capacity costs in 2030, and two to three times as much in 2050 even with high deployment of renewable energy. Our research finds that net peak load drops 31–46% in 2030 and 39–86% in 2050, depending on region. These results hold regardless of the speed of renewable energy deployment, though we find that energy efficiency is likely to be more valuable in avoiding total electricity system costs under a more rapid supply-side decarbonization scenario. Though our analysis did not examine the effects on distribution costs, energy efficiency deployment will help reduce or delay increased distribution system costs. Energy efficiency may also help mitigate many of the challenges associated with high levels of large-scale renewable energy deployment, including critical materials mining, land acquisition, transmission siting, long renewable energy interconnection queues, and carbon capture and sequestration.

Measures that reduce thermal space conditioning load (i.e., envelope, HVAC, and smart thermostat) are likely to have the greatest long-run impact, though the specific benefits will vary regionally. We find greater near-term potential for commercial measures, but more potential for residential savings by mid-century across the country. Energy efficiency will not only continue to deliver strong savings in the context of a high renewable future but will likely enable the grid to arrive at this future sooner and more reliably.

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Appendix A—Quantitative Analysis Additional Details

This appendix contains additional details regarding this report's quantitative analysis. First, the software and modeling assumptions used to quantify the power sector impacts of EE measures and packages are summarized. Next, the energy efficiency measures developed through the Scout modeling software and utilized in our quantitative analysis are summarized. Then, additional details regarding avoided costs as reported through Cambium are provided. Finally, details on how these two datasets were aligned within this report are presented.

DEMAND-SIDE AND POWER SYSTEM MODELING

LBNL and NREL have contributed to our understanding of the impacts of EE through the development and use of the Scout software tool. Scout is a demand-side modeling tool capable of representing the impacts of efficiency, flexibility, and fuel-switching measures on building demand.[31] Users of the tool can construct scenarios combining these demand-side measures through 2050. The scenarios can be constructed in the context of individual measure-level characteristics (e.g., cost, performance, lifetime, and how those are exposed to consumers) and policy-related levers, such as appliance standards and codes that establish the technology floor available to consumers on the market. Scout can also integrate assumptions about the role of breakthrough efficiency technologies coming into market in future years.

Scout can analyze a range of dynamics related to EE, including early retrofits (i.e., accelerated stock turnover) and getting efficiency measures into the market more quickly by incentivizing people to replace their equipment before the end of its useful life. Through an investigation of multiple scenarios, Scout can explore different sensitivities, levels of decarbonization, and demand-side measure deployment. The tool can then translate those into hourly load profiles at the grid region level.

Capacity expansion models are capable of examining how power sector policies, fuel prices, technology availability, and other factors impact medium- and long-term generation and capacity mixes.[32] They help address issues like the cost implications of decarbonization

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[31] Scout utilizes exogenous forecasts of electrification rates that come from a Guidehouse analysis conducted as part of DOE Building Technology Office's E3 initiative (Office of Energy Efficiency & Renewable Energy 2022).

[32] In addition to GridSim, a number of additional capacity expansion models exist such as the National Energy Modeling System (NEMS), Regional Energy Deployment System (ReEDS), Integrated Planning Model (IPM), Haiku, and MARKet Allocation (MARKAL). None of these options has emerged as a consensus standard among experts.

pathways, the impacts of fuel price fluctuations, the change in consumption and expenditures, and the outcomes of energy and environmental policies.

Capacity expansion models are typically capable of outputting data on annual generation from the suite of supply-side resources, generation capacity by plant type, transmission expansion, fuel consumption, electricity prices, emissions, and more. They provide aggregated snapshots of what the grid of the future could look like. However, they are usually not detailed enough to produce generation commitment chronologically for every hour of the year. That more granular scheduling is typically accomplished through production cost models.

ENERGY EFFICIENCY MEASURES

Hourly baseline and efficient load profiles used in this report are drawn from a publicly released dataset created by Langevin et al. (2021). A full detailed description of the efficiency measures is available from the supplemental information paper associated with their research.

Representative normalized building-level load shapes are developed via EnergyPlus simulations along several dimensions. The following are the dimensions and options utilized in this report:

- **Measure scenario**. Four measure scenarios are considered: baseline residential and commercial cases in which no measures are implemented, and residential and commercial measure sets with energy efficiency measures deployed.
- **Building type**. Six building types are considered: single-family homes are modeled for residential buildings, and five building types are modeled for commercial buildings. In 2020, single-family homes represent 84% of residential square footage and 82% of electricity use, and were therefore deemed to be a suitable building type to represent the normalized load shape characteristics of the residential stock as a whole. Commercial building use types and normalized load patterns are more diverse than residential and therefore require a larger set of representative building types. The five commercial building types are:
    - Large office
    - Large hotel
    - Medium office
    - Standalone retail
    - Warehouse
- **End use**. Twelve end uses are considered: seven end uses (heating, cooling, lighting, water heating, refrigeration, plug loads, and miscellaneous/other) are common to the residential and commercial models; four end uses (clothes washing, clothes drying,

dishwashing, and pool heaters and pumps) are unique to the residential models; and one end use (ventilation) is unique to the commercial models.

- **Climate location**. U.S. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) 90.1-2016 climate zones are considered through simulations in representative cities for each climate zone. Note that in commercial buildings, only thermally related loads (cooling, ventilation, and heating) are broken out by climate zone.

AVOIDED COSTS

The quantitative analysis conducted for this research report draws from Cambium marginal avoided cost modeling. More specifically, we look at avoided energy costs and avoided capacity costs. We have included the following descriptions of these data fields from the Cambium documentation for reference (Gagnon et al., 2021):

- **energy_cost_enduse**: This metric reports the short-run marginal costs of providing the energy for a marginal increase in load, in $/MWh of end-use load. These metrics are derived using the shadow price off of an energy constraint in the PLEXOS model.[33] They include short-run costs that vary as a function of load (fuel and variable costs), but they do not reflect other operational costs that are fixed or vary as "steps," such as start-up costs or fixed operation and maintenance costs.

  These metrics are conceptually similar to a day-ahead locational marginal price. Specifically, the coarse geographic resolution, lack of temperature effects on generator heat rates and transmission losses, and the fact that these are derived from the shadow prices out of a system-wide least-cost optimization model, all contribute to these marginal costs tending to be less variable than observed prices in energy markets.

  These marginal costs include the effects of generator short-run marginal costs, inter-balancing authority (BA) transmission losses, inter-BA transmission congestion, and distribution loss effects. Cost recovery for start-up costs is not reflected in these values, as these are marginal costs and start-up costs are step changes. Debt service and fixed operations and maintenance costs are likewise not reflected in these marginal costs.

  As a least-cost optimization model, PLEXOS can sometimes find solutions that result in exceptionally high marginal costs. For example, PLEXOS will sometimes drop a small amount of a reserve product and incur the associated penalty rather than incur the costs of starting up a generator that could have provided those reserves. This results in the

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[33] PLEXOS is a utility-scale capacity expansion model. Shadow pricing is a method of investment or decision analysis that adds a hypothetical surcharge to market prices for goods or services to account for abstract or intangible commodities not traded in the marketplace. In this case, the shadow price simulates a carbon price as a means of inducing a national decarbonization policy trend within the model. These higher-cost carbon resources are reported as marginal costs.

marginal energy cost being set by the $/MWh penalty for dropping the reserve product in that hour. Though this is a technically correct description of the least-cost solution, we feel these marginal cost spikes are not useful descriptions of the situation and are not generally helpful for the types of analyses for which Cambium data are used.

Therefore, for each BA and each time step, we cap the marginal energy costs at the short-run marginal cost (plus an adder for start-up cost recovery) of the least-expensive natural-gas combustion turbine (NGCT) that has available capacity in that BA. When there is no NGCT in the BA with remaining capacity, the SRMC plus start-up adder of the most expensive NGCT in the conterminous United States is used as a cap. The models that Cambium draws from are not set up to assess resource adequacy or reliability, and the implementation of these price caps reflects that limitation.

For the Mid-case 95% decarbonization by 2050 and Mid-case 95% decarbonization by 2035 scenarios in the 2021 Cambium release (which both include national carbon constraints), the shadow price on the carbon constraint for the corresponding year in the underlying ReEDS model run is added to the operating costs of emitting generators for the corresponding PLEXOS run. This tends to meaningfully increase the marginal energy costs in the decarbonization scenarios.

- **capacity_cost_enduse**: This metric reports the long-run cost of additional capital investment (in units of $/MWh) necessary to maintain a target planning reserve margin when demand is increased. An annual marginal capacity cost is derived from the shadow price off of the capacity constraint in the ReEDS model, which is set by the least-cost option for obtaining a marginal increase in firm capacity within each BA. The increase in firm capacity can be achieved by building new generation capacity, by holding on to existing generation capacity that would otherwise have been retired, or by building new inter-BA transmission capacity, whichever is the least-cost solution.

  The annual shadow price is then increased by the planning reserve margin and allocated to the highest net load hours within the year. The use of net load is a heuristic for identifying the hours with the highest loss of load probability, and therefore the hours in which increased demand would induce a need for more firm capacity.

  A region can have a marginal capacity cost of zero for a year if the capacity constraint was not binding for that year (i.e., the available firm capacity exceeded what was required by the region’s planning reserve margin and peak load).

ALIGNING DEMAND- AND SUPPLY-SIDE DATASETS

The geographic boundaries of the Electricity Market Module regions used to aggregate Scout data and the boundaries of the GEA regions (see figure A1) used to generate Cambium data (see figure 14) are similar, but not identical. We provide a map that links the two sets of regions together in our analysis in table A1, along with the weather stations used to represent those regions in the selection of representative peak days.

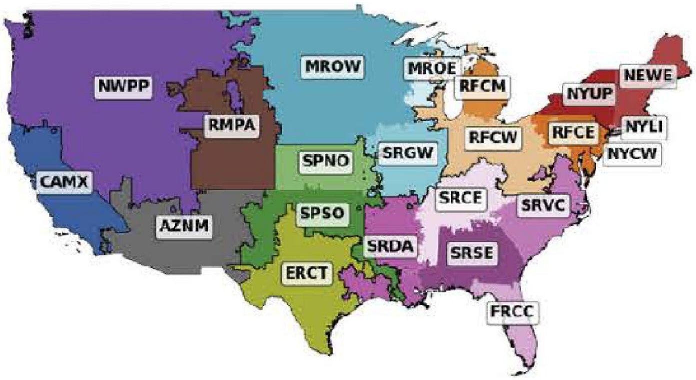

Figure A1. Regional boundaries applied to generate and aggregate Scout results used in this report. Figure sourced from Langevin et al. (2021).

Table A1. Regional identifiers used to analyze Scout and Cambium data in combination

Scout EMM	Cambium GEA	Weather Station — NOAA Station Numbers
ERCT	ERCT	Fort Worth Meacham Intl AP — 747390
CAMX	CAMX	Bakersfield/Meadow — 723840
NWPP	NWPP	Boise Air Terminal — 726810
RFCW	RFCW	Dayton International Airport — 724290
SRSE	SRSO	Atlanta Hartsfield International AP — 722190

The third column contains the weather station (with National Oceanic and Atmospheric Administration station numbers) used to identify representative peak days.

Scout and Cambium data are generated using different weather profiles. While Cambium uses real 2012 weather data, Scout uses typical meteorological year (TMY3) data, which are less extreme by design. However, energy savings amounts and avoided electric system costs are both correlated to exterior temperature. For example, demand—and energy savings—are higher on very hot days as air-conditioning load peaks. These days also happen to contain some of the highest demand hours of the year, which leads to high electricity system costs. Failure to account for this correlation could erode the connection between Scout's hourly energy savings estimates and Cambium's hourly avoided costs.

To mitigate this issue, we adopt the following process to study representative peak days within our analysis. For each region, we identify within Cambium one of the highest cost days of the year (in terms of total avoided marginal costs). We extract the hourly temperature profile for that day in 2012, then find a nearby day within the TMY3 dataset that has the lowest root mean square difference in hourly temperature with the 2012 Cambium weather day.[34] Weather stations were selected to strike a balance between being closely located to regional population centers and being geographically central to the region as a whole (see table A2).

The data in table A2 indicate which days within the Cambium dataset we are using to represent peak summer and winter days for each region in 2030 and 2050.[35] While all regions have days we would conventionally accept as peak summer days, not all regions have peak winter days. The CAMX region, for example, has relatively flat and low projected wholesale prices during winter months. For completeness, we identify peak winter days in these cases as well, but acknowledge that the avoided costs during those days will be quite low.

Table A2. High-cost days on the electricity system selected from Cambium to conduct our peak day analysis

GEA Region	Cambium 95x2050 (2030)		Scout TMY3	
	Summer	Winter	Summer	Winter
CAMX	August 14	December 17	August 3	December 31
ERCT	June 27	December 11	July 12	December 13
NWPP	June 22	January 13	June 23	January 26
RFCW	July 7	January 25	July 22	January 12
SRSO	June 29	January 4	July9	January 16

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[34] In this context, we define "nearby" to be within 16 days of the Cambium high-cost day. This number of days was selected as a compromise between considering a large number of potential TMY3 weather days and getting so far away that the resulting Scout load profiles are no longer representative of the Cambium high-cost day.

[35] Not all days in analyzed in table A2 resulted in figures shared in this report. However, results from those days are available upon request.

GEA Region	Cambium 95x2035 (2030)		Scout TMY3	
	Summer	Winter	Summer	Winter
CAMX	August 14	January 2	August 3	January 18
ERCT	June 17	December 28	July 12	December 12
NWPP	July 11	January 13	July 21	January 26
RFCW	July 7	January 19	July 22	January 27
SRSO	July 1	January 4	July 8	January 16

GEA Region	Cambium 95x2050 (2050)		Scout TMY3	
	Summer	Winter	Summer	Winter
CAMX	August 9	December 16	July 28	December 1
ERCT	June 26	December 27	July 12	December 13
NWPP	August 9	January 12	July 29	December 29
RFCW	July 7	January 25	July 22	January 12
SRSO	July 1	January 4	July 8	January 16

GEA Region	Cambium 95x2035 (2050)		Scout TMY3	
	Summer	Winter	Summer	Winter
CAMX	August 18	January 2	August 3	January 18
ERCT	June 26	December 27	July 12	December 13

GEA Region	Cambium 95x2035 (2050) Summer	Winter	Scout TMY3 Summer	Winter
NWPP	August 12	January 12	July 27	December 29
RFCW	July 7	January 25	July 22	January 12
SRSO	July 1	January 4	July 8	January 16

For each year and renewable energy scenario, a peak day is selected in summer and winter for each region. The final two columns contain the days chosen from the TMY3 dataset from which to draw (from Scout) the energy savings load profiles associated with the Cambium peak days.

The tables above also indicate which TMY3 days we are using to represent comparable days within the Cambium dataset. To select a comparable TMY3, we consider any day within 16 days of the 2012 Cambium days. We then select the TMY3 day that has the lowest root mean square difference in hourly temperature with the 2012 Cambium weather days.

We employ a similar process to identify TMY3 weather days that most closely matched days containing each region's highest net load hour of the year. Those results are reported in table A3. Coincidentally, the Cambium peak net load days did not differ by renewable energy scenario in either 2030 or 2050.

Table A3. Peak net load days in Cambium in 2030 and 2050 (columns 2 and 3, respectively) and the TMY3 weather days that most closely matched the peak net load days' temperature profiles (columns 4 and 5).

GEA Region	Cambium peak net load days 2030	2050	Scout TMY3 comparable weather days "2030"	"2050"
CAMX	August 14	October 2	August 3	October 1
ERCT	August 31	June 26	August 25	July 12
NWPP	August 17	August 17	August 10	August 10
RFCW	July 7	July 7	July 22	July 22
SRSO	June 30	July 1	July 7	July 8

In our peak net load days analysis, we grouped the generating resources in Cambium into three categories for the purpose of plotting generation profiles: renewable, nonrenewable, and nuclear. The "renewable" category includes wind, solar, hydroelectric, geothermal, and biomass. The “nonrenewable” category includes coal, natural gas, and oil-gas-steam. We assumed that renewable resources would always be used first, unless nuclear generation was required to meet the balance of demand. In that case, we assumed all nuclear energy would be utilized, with renewable energy being curtailed or directed to storage. The remaining balance of demand was assumed to be met with nonrenewable resources.

Because our analysis draws from two distinct datasets (i.e., Scout and Cambium) that were generated under different sets of assumptions, we encountered inconsistencies in assumed demand levels. This led to instances in which Cambium reported generating resources creating more or less energy than Scout assumes would be needed under baseline conditions.

To manage this inconsistency, we prioritize the elements of the analysis that would take precedence in the real world or which energy efficiency implementers would have a measure of control over. To that end, we prioritize Scout’s assumptions about baseline load and load after energy efficiency measures are implemented, followed by Cambium’s assumptions about the level of renewable energy generation that would be available to meet it. Because the amount of renewable energy reported in Cambium is a function of the decarbonization constraints (i.e., either 95x2035 or 95x2050), and because that energy would almost certainly be utilized first, we assumed the remainder of load would be served by nonrenewable sources, even when that amount was in disagreement with Cambium’s reported nonrenewable generation. In reality, this discrepancy would be addressed through policies like resource adequacy requirements or capacity auctions.

Finally, we caution the reader that there are load modeling discrepancies between Scout and Cambium data that we are unable to correct for in this analysis. The ReEDS capacity expansion model that creates the Cambium data generates total hourly system loads using assumptions about building sector load that differ from those represented in the EnergyPlus models that generate Scout data.[36] While both the weather and load discrepancies reduce the precision of our conclusions, they are unlikely to be substantial enough to influence our central conclusions about the value of particular types of EE measures in a high renewable energy future.

Another potential limitation of our analysis concerns carbon leakage and its influence on energy efficiency. Factors like utility self-scheduling and electricity imports can make the electric grid more or less carbon intensive in practice than in theory. Energy efficiency offers the benefit of reducing consumption, regardless of the providence of the generated electricity. We do not account for these benefits in this analysis.

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[36] For example, ReEDS uses older hourly end-use load allocations (Brown et al. 2020).

Appendix B–Additional Results

This appendix contains additional avoided cost and other results not presented in the main body of the report.

Figure B1 through figure B3 report the annual marginal avoided costs achieved by each energy efficiency measure or package in the CAMX, NWPP, and SRSO regions under the 95x2050 scenario.

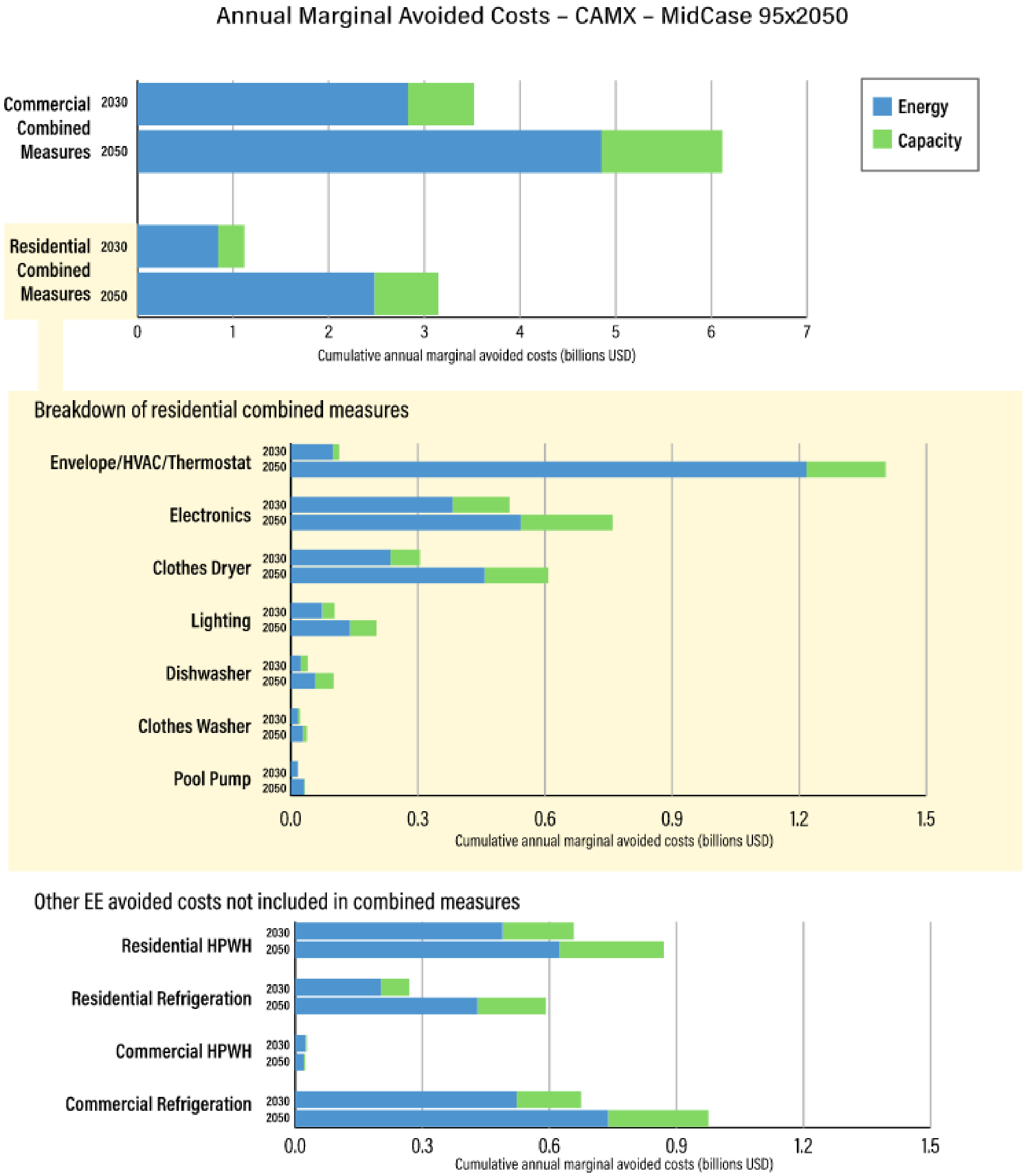


Figure B1. Annual marginal avoided costs in California (CAMX) in the MidCase 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs.

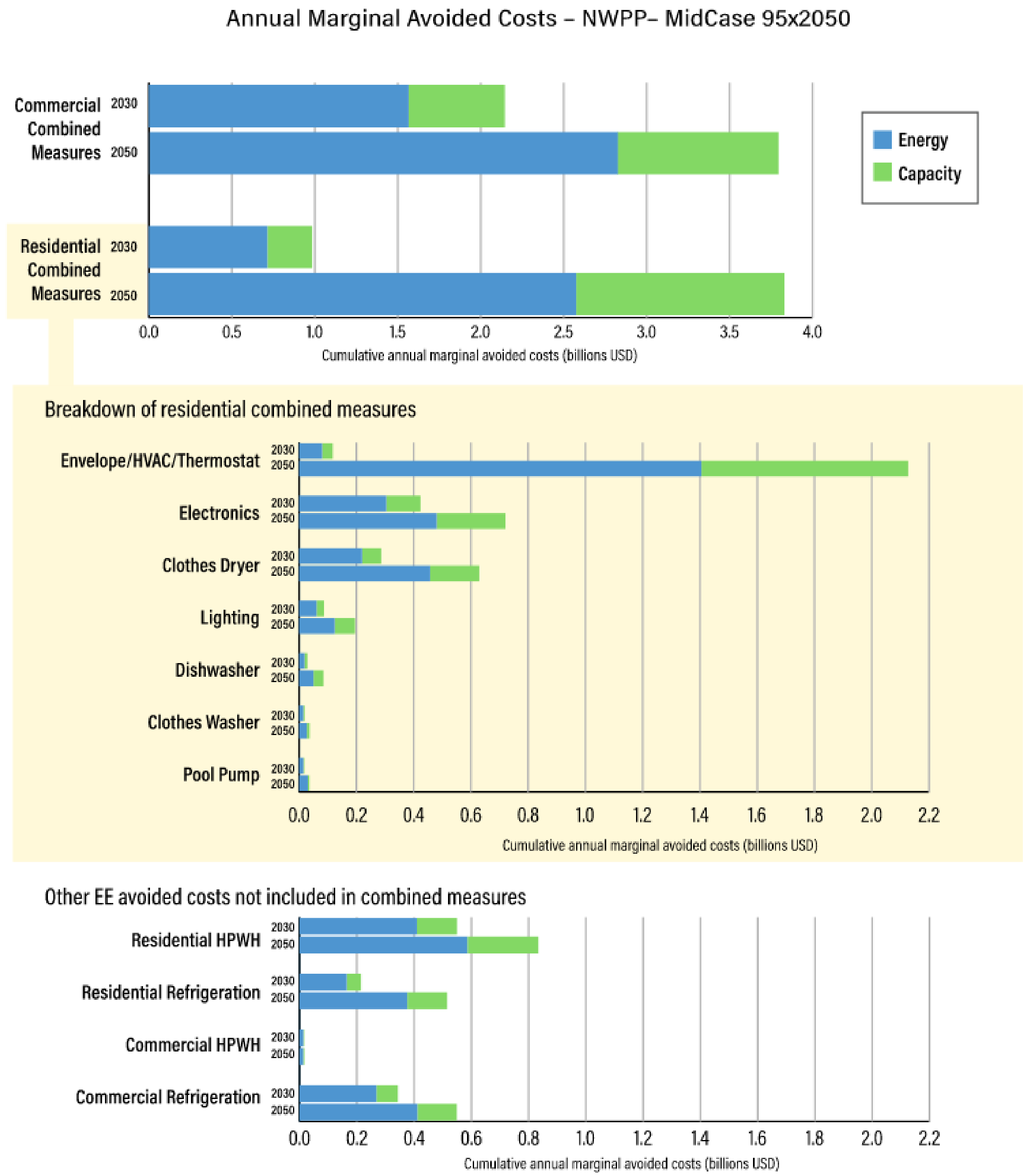


Figure B2. Annual marginal avoided costs in the Pacific Northwest (NWPP) in the MidCase 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs.

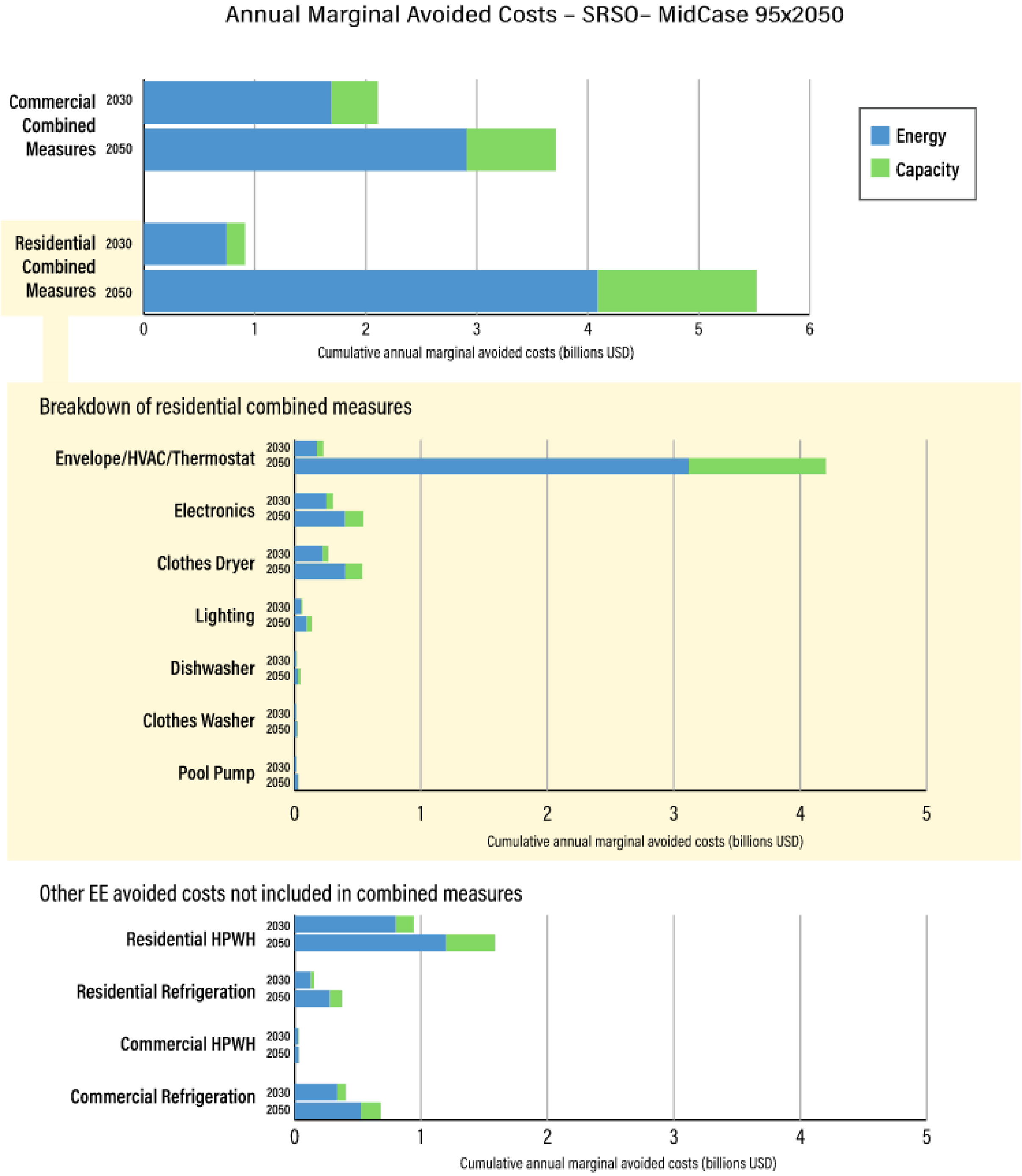


Figure B3. Annual marginal avoided costs in the Southeast (SRSO) in the MidCase 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs.

Figure B4 through B8 report the annual marginal avoided costs achieved by each energy efficiency measure or package in the 95x2035 scenario.

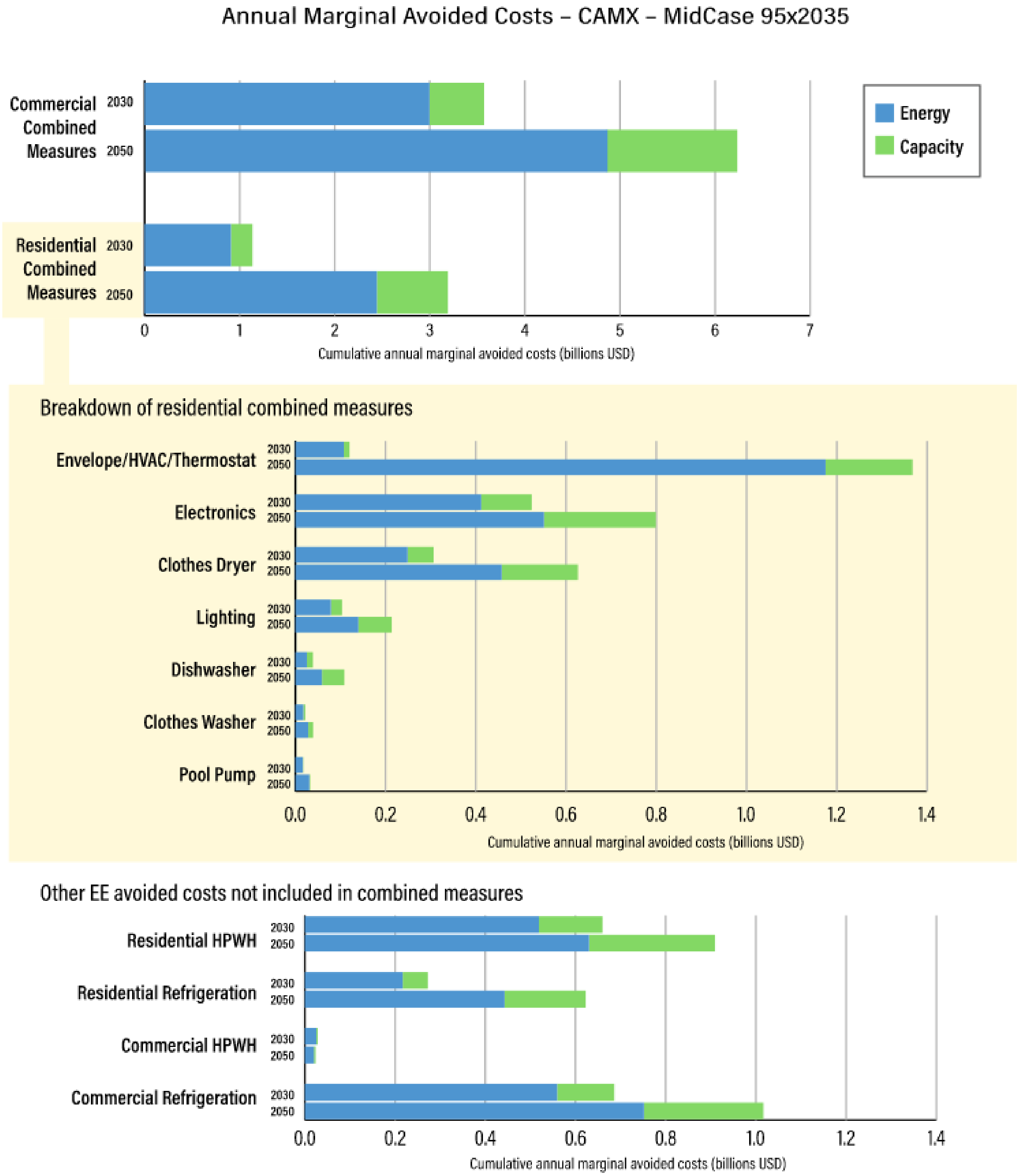


Figure B4. Annual marginal avoided costs in California (CAMX) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs.

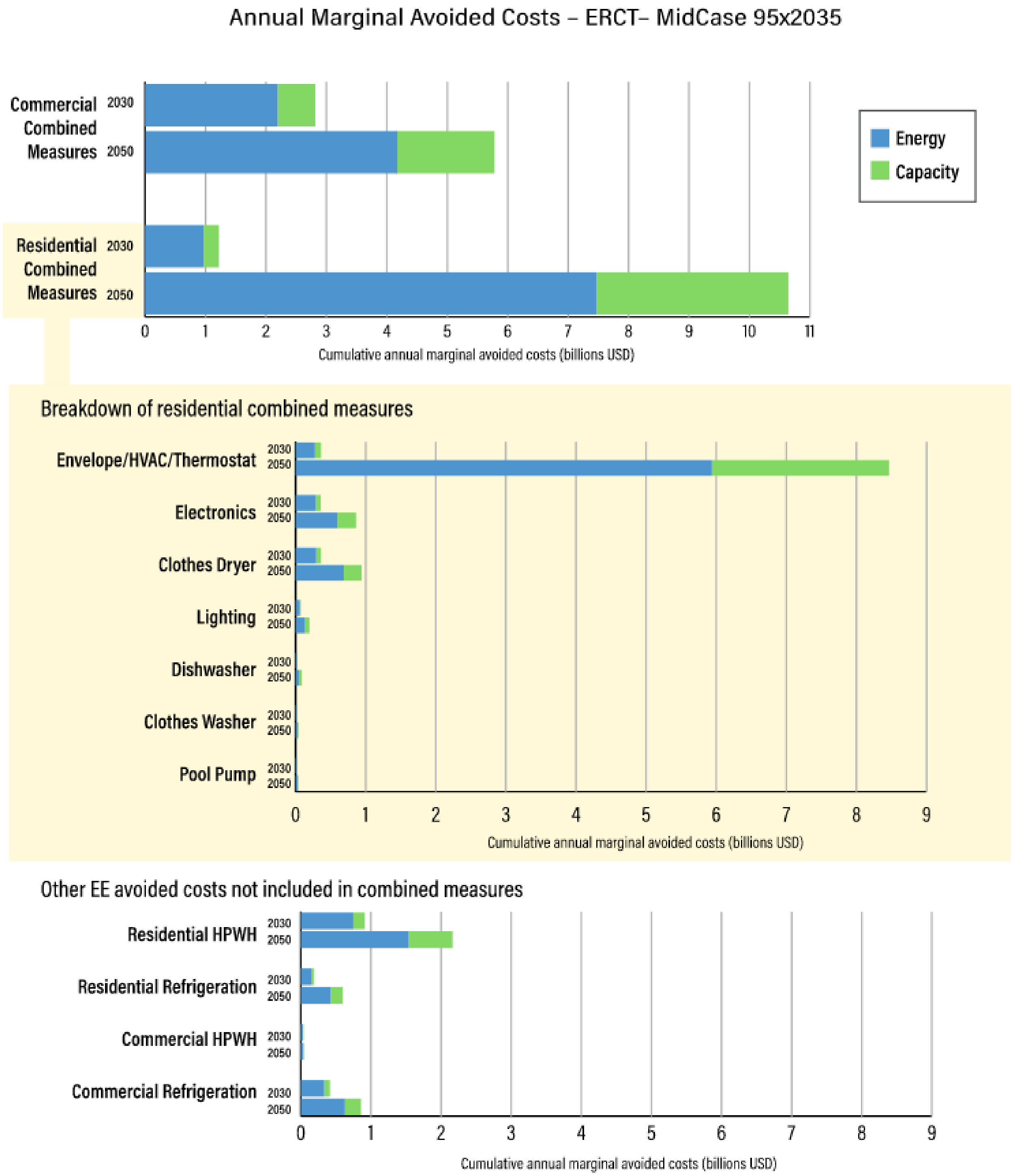


Figure B5. Annual marginal avoided costs in Texas (ERCT) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs.

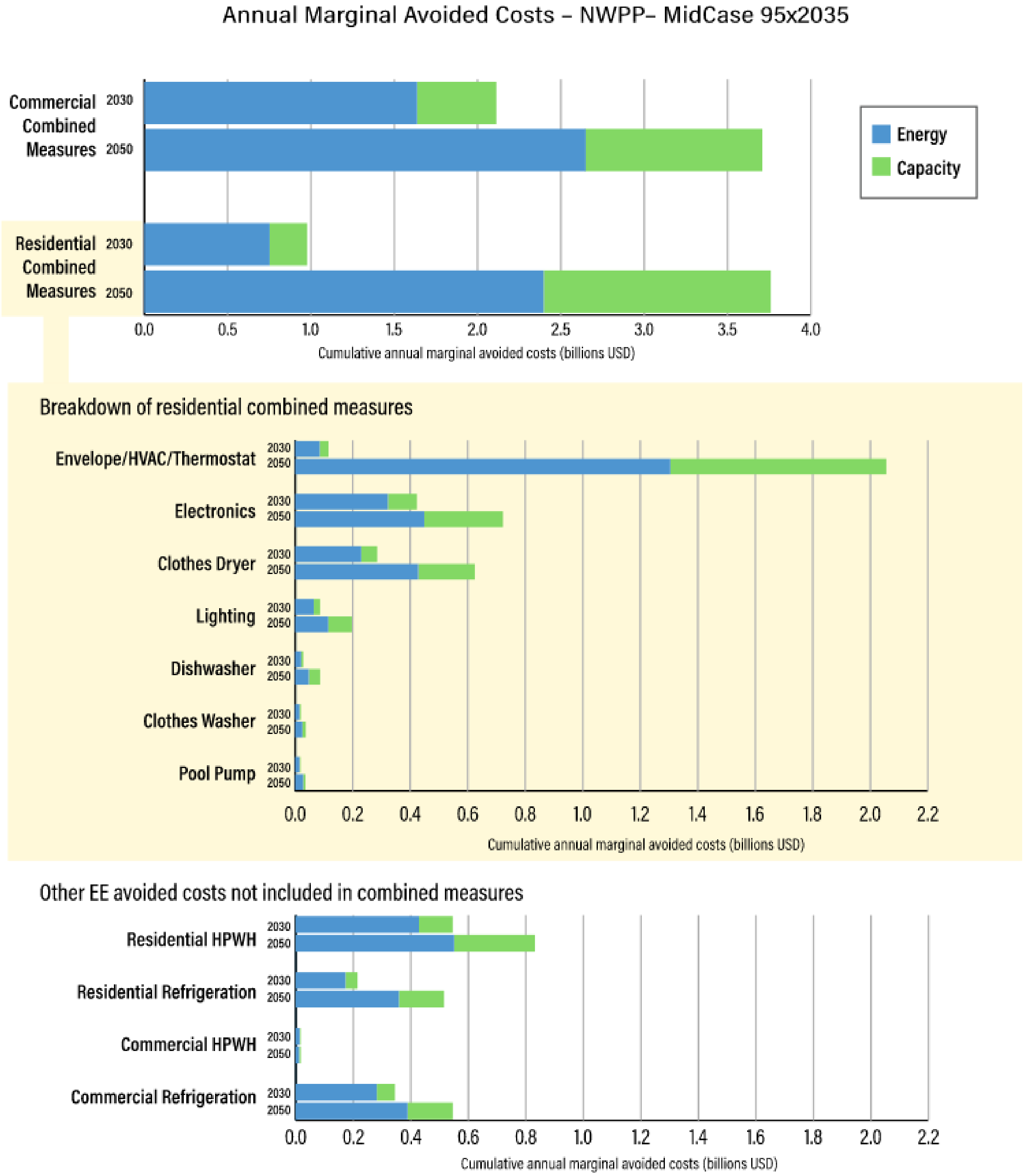


Figure B6. Annual marginal avoided costs in the Pacific Northwest (NWPP) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs.

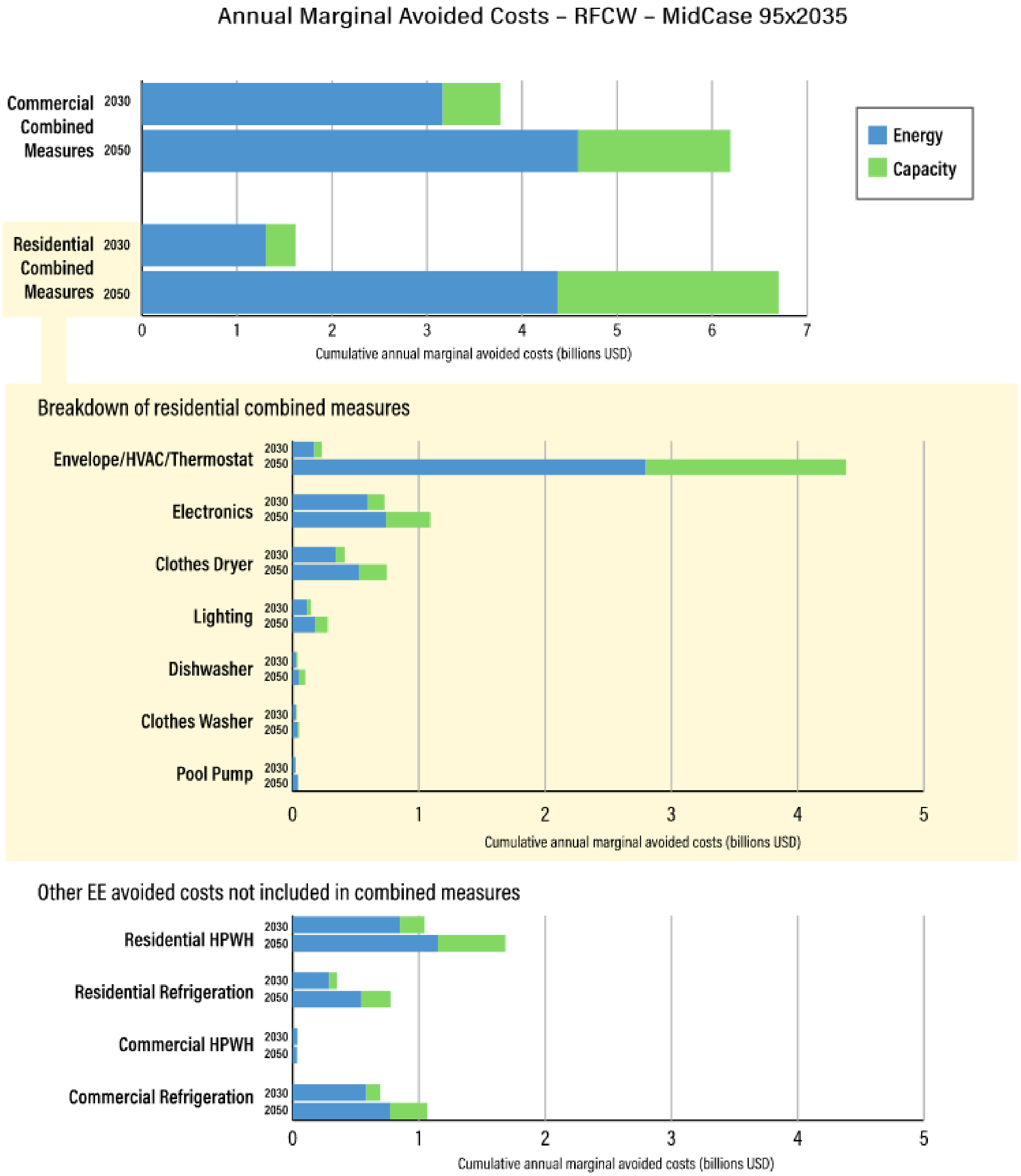


Figure B7. Annual marginal avoided costs in the Midwest (RFCW) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs.

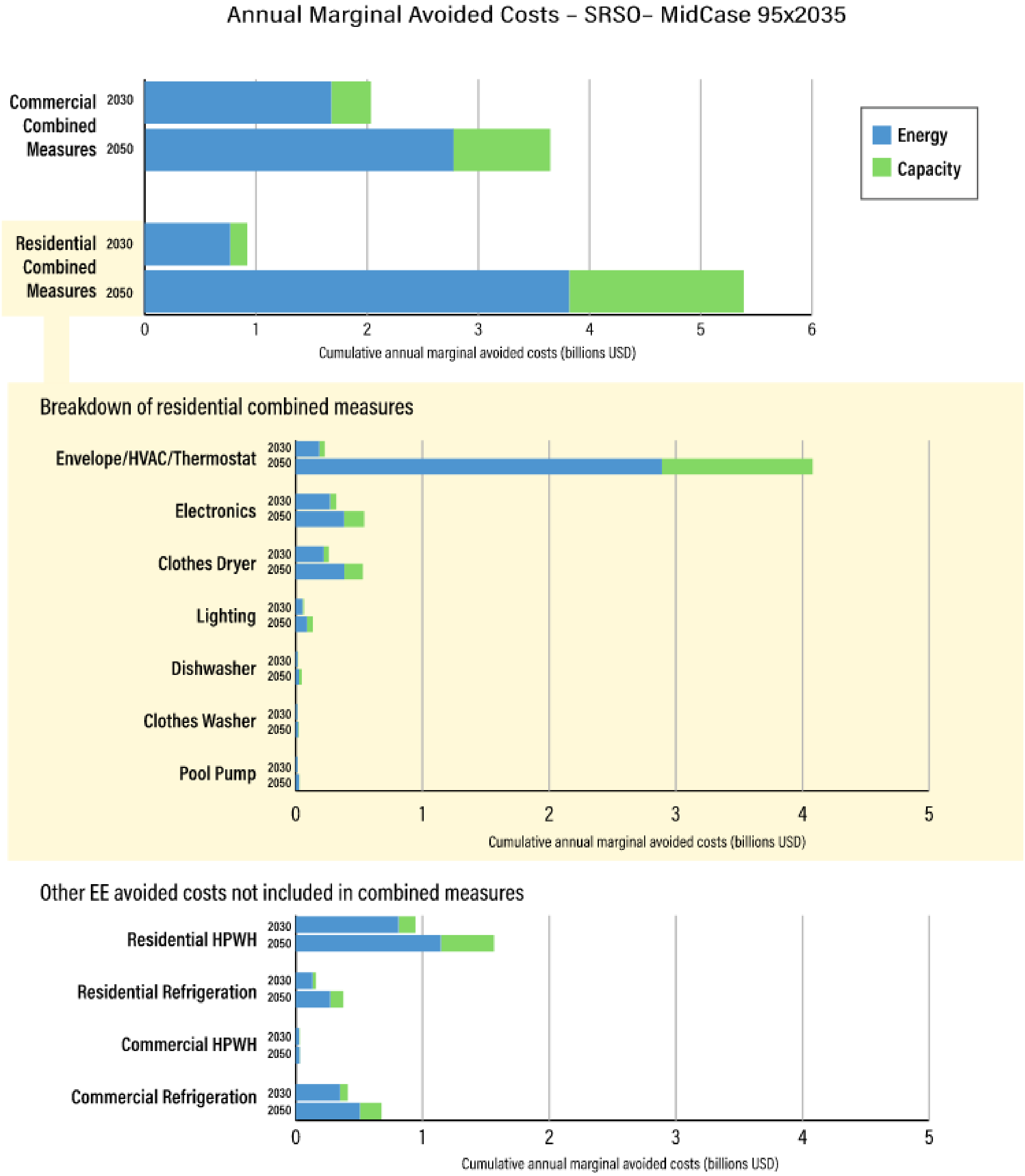


Figure B8. Annual marginal avoided costs in the Southeast (SRSO) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs.

In table B1, we present the sum of the annual marginal avoided costs in 2030 and 2050 under the 95x2035 renewable energy scenario. These results are disaggregated into their residential and commercial contributions in table B2, and are visualized in figure B9. These two tables are the analogs of table 5 and table 6 in the main body of the report.

Table B1. Sum of marginal electricity system costs (in billions of dollars) avoided in 2030 and 2050 by energy efficiency measures/packages in Table 3 for the 95x2035 scenario.

Region	2030	2050	% Change
CAMX	$6.355	$11.994	+89%
ERCT	$5.592	$20.089	+259%
NWPP	$4.212	$9.376	+123%
RFCW	$7.521	$16.464	+119%
SRSO	$4.497	$11.683	+160%

Table B2. Same information as in table B1, but broken out by the residential contribution (left) and the commercial contribution (right).

Region	2030	2050	% Change
CAMX	$2.067	$4.720	+128%
ERCT	$2.325	$13.408	+477%
NWPP	$1.738	$5.106	+194%
RFCW	$3.014	$9.165	+204%
SRSO	$2.022	$7.328	+262%

Region	2030	2050	% Change
CAMX	$4.288	$7.273	+70%
ERCT	$3.267	$6.680	+104%
NWPP	$2.474	$4.271	+73%
RFCW	$4.507	$7.299	+62%
SRSO	$2.474	$4.355	+76%

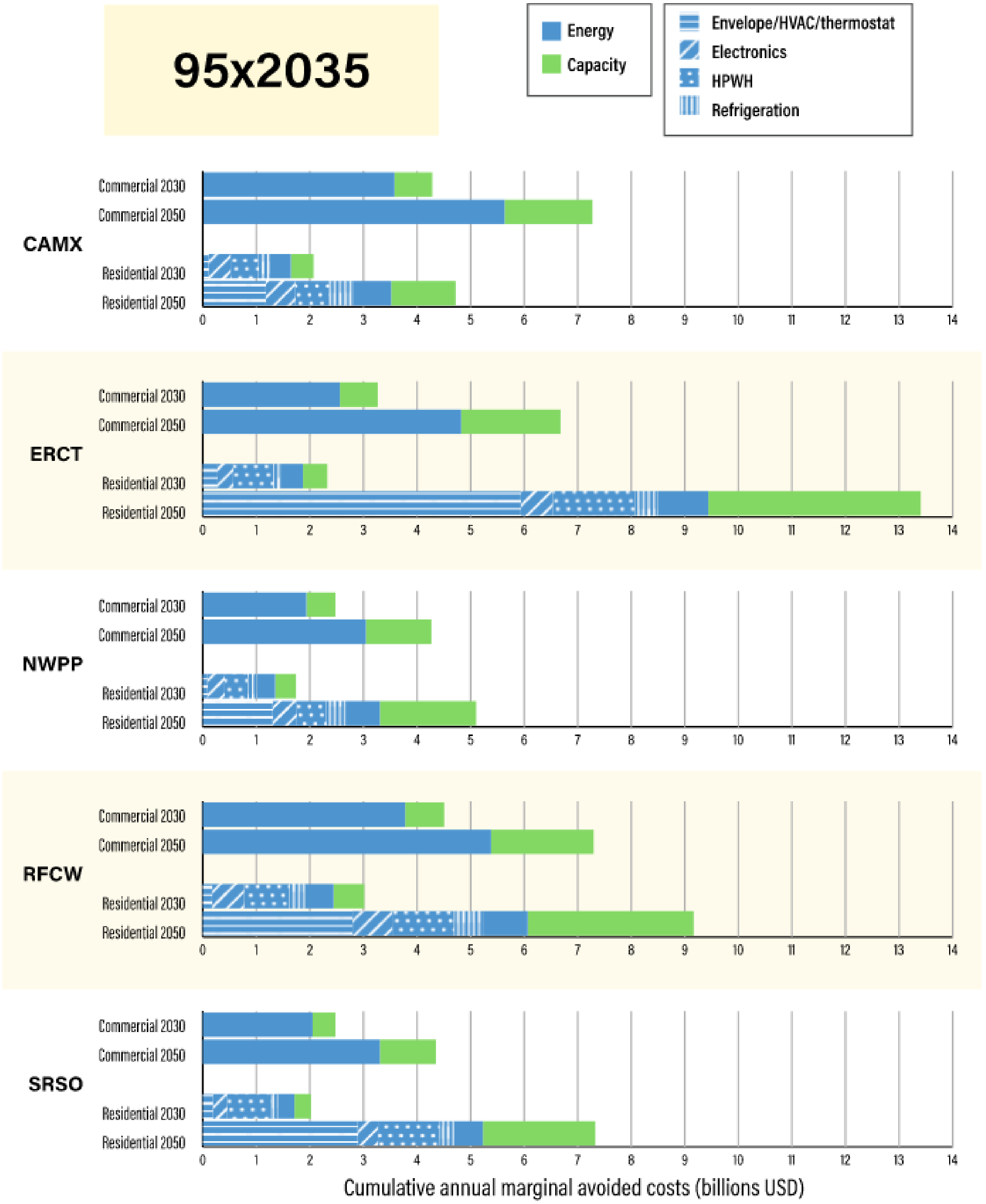


Figure B9. Sum of annual marginal avoided electricity system costs achieved by our set of EE measures and packages in the 95x2035 renewable energy scenario. Avoided costs are separated by residential and

commercial sector. Four of the largest avoided cost drivers (i.e., envelope/HVAC/thermostat, electronics, HPWH, and refrigeration) are broken out for the residential sector. Because of the interactive effects of commercial EE measures, a similar breakdown was not possible for the commercial sector.

Tables B3 and B4 report the avoided costs achieved by each component of our residential envelope/HVAC/thermostat package under the 95x2050 and 95x2035 renewable energy scenarios, respectively. Each component affects a unique, non-overlapping set of buildings such that the avoided costs achieved by our thermal space conditioning EE package equals the sum of these three components.

Table B3. Avoided costs achieved by each of our residential envelope/HVAC/thermostat package components under the 95x2050 renewable energy scenario

			2030			2050	
Region	Component	Energy	Capacity	Portfolio	Energy	Capacity	Portfolio
CAMX	ASHP	$64,661,923	$3,247,408	$360,495	$783,844,723	$41,178,883	$0
	CAC	$21,746,575	$10,257,768	$121,159	$278,867,546	$126,840,338	$0
	Env./Therm.	$12,823,983	$1,544,740	$71,710	$154,692,132	$18,616,016	$0
ERCT	ASHP	$216,474,429	$76,395,532	$0	$4,360,002,406	$1,414,068,985	$0
	CAC	$67,445,344	$52,921,659	$0	$1,473,622,289	$719,672,711	$0
	Env./Therm.	$8,816,371	$4,948,985	$0	$178,920,737	$59,594,126	$0
NWPP	ASHP	$37,629,881	$13,917,560	$0	$551,982,918	$222,092,605	$0
	CAC	$23,167,707	$15,729,076	$0	$542,695,617	$367,471,589	$0
	Env./Therm.	$19,794,646	$7,458,420	$0	$310,774,826	$132,118,904	$0
RFCW	ASHP	$28,643,874	$2,990,179	$0	$372,871,121	$65,890,960	$94,306
	CAC	$89,124,878	$94,267,364	$0	$1,553,501,481	$1,208,553,325	$278,394
	Env./Therm.	$55,907,445	$34,940,749	$0	$858,393,621	$279,912,019	$177,556
SRSO	ASHP	$119,058,995	$20,678,095	$0	$1,993,260,401	$480,712,660	$0
	CAC	$51,007,886	$26,975,245	$0	$977,947,646	$557,547,844	$0
	Env./Therm.	$8,376,672	$2,606,461	$0	$147,226,354	$45,357,948	$0

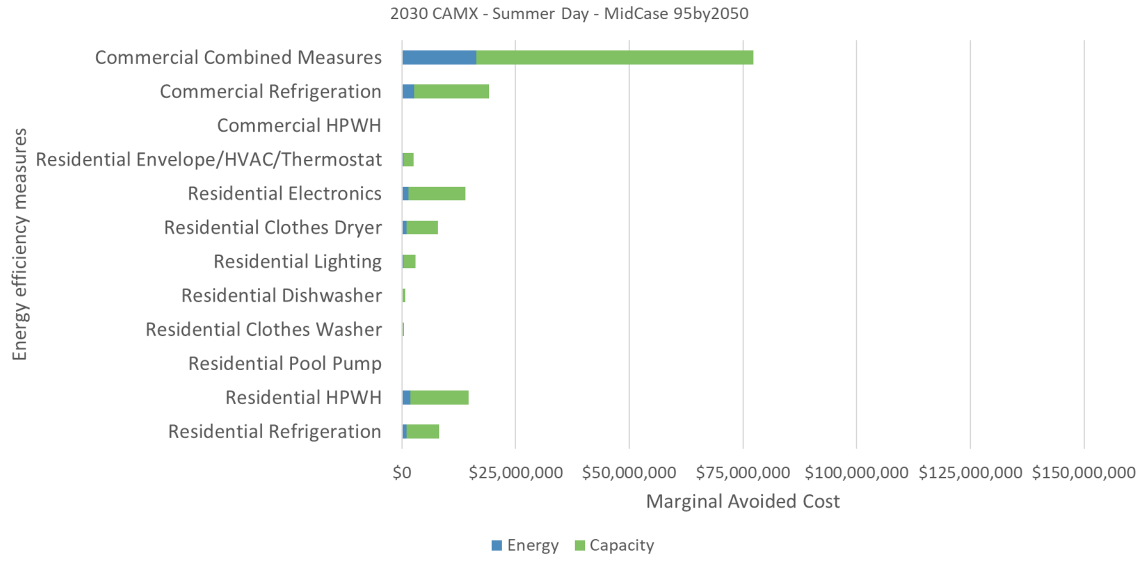
In the Component column, ASHP = Residential ASHP/ICT/Envelope, CAC = Residential CAC/ICT/Envelope, and Env./Therm. = Residential ICT/Envelope.

Table B4. Avoided costs achieved by each of our residential envelope/HVAC/thermostat package components under the 95x2035 renewable energy scenario

		2030			2050		
Region	Component	Energy	Capacity	Portfolio	Energy	Capacity	Portfolio
CAMX	ASHP	$70,133,571	$2,718,565	$17,166	$745,637,008	$43,731,677	$0
	CAC	$23,319,706	$8,612,038	$5,769	$280,150,693	$130,696,888	$0
	Env./Therm.	$13,867,201	$1,296,165	$3,415	$149,535,162	$18,588,095	$0
ERCT	ASHP	$200,990,055	$49,484,463	$0	$4,347,254,972	$1,568,026,980	$0
	CAC	$67,552,546	$34,255,925	$0	$1,415,668,360	$888,160,327	$0
	Env./Therm.	$8,557,912	$3,045,582	$0	$174,966,469	$73,697,908	$0
NWPP	ASHP	$39,955,007	$11,576,474	$0	$500,712,593	$244,746,022	$0
	CAC	$24,510,617	$12,904,625	$0	$518,603,217	$370,922,433	$0
	Env./Therm.	$20,997,737	$6,176,727	$0	$285,053,387	$135,831,868	$0
RFCW	ASHP	$29,292,962	$1,838,068	$0	$392,063,093	$68,252,104	$94,306
	CAC	$85,239,156	$46,938,619	$0	$1,537,122,182	$1,239,409,151	$278,394
	Env./Therm.	$55,354,592	$13,495,013	$0	$866,618,719	$280,309,827	$177,556
SRSO	ASHP	$126,473,690	$17,648,193	$0	$1,838,254,738	$529,819,141	$0
	CAC	$50,608,450	$23,260,777	$0	$915,439,578	$611,833,348	$0
	Env./Therm.	$8,526,132	$2,119,733	$0	$136,238,161	$50,283,889	$0

In the Component column, ASHP = Residential ASHP/ICT/Envelope, CAC = Residential CAC/ICT/Envelope, and Env./Therm. = Residential ICT/Envelope.

Figures B10 through B12 contain representative peak day marginal avoided cost results for the three regions not covered in the main body of the report: California, Texas, and the Northwest. Results are presented in 2030 and 2050 for the 95x2050 scenario. Note that of the five regions studied in this report, only the Northwest experiences peak day costs during the winter season.



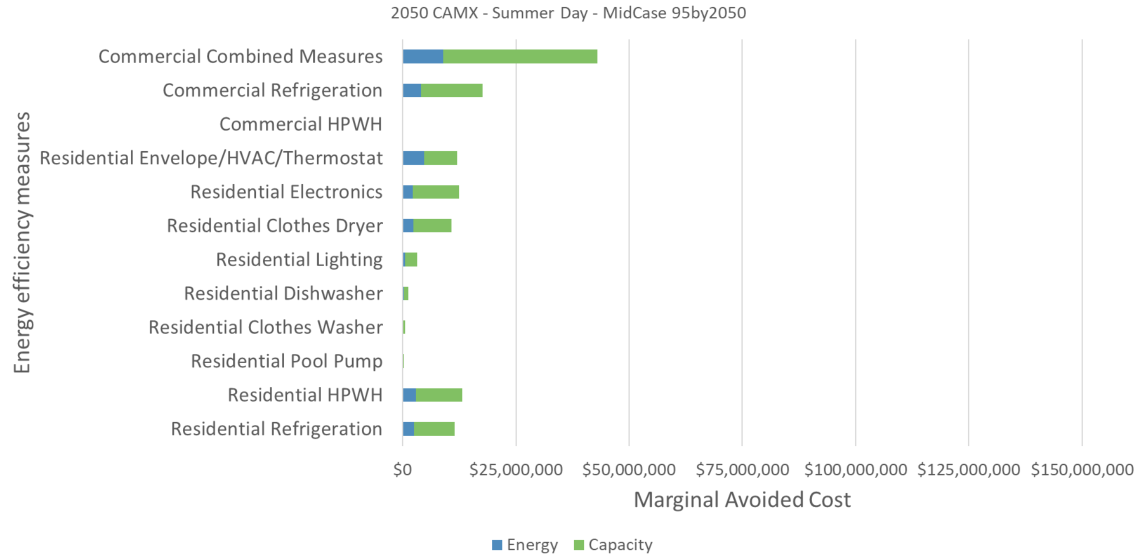


Figure B10. Summer peak day marginal avoided costs in California (CAMX) in the MidCase 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs are drawn from August 14 (2030) and August 9 (2050) within Cambium, while energy savings are drawn from August 3 (2030) and July 28 (2050) within Scout.

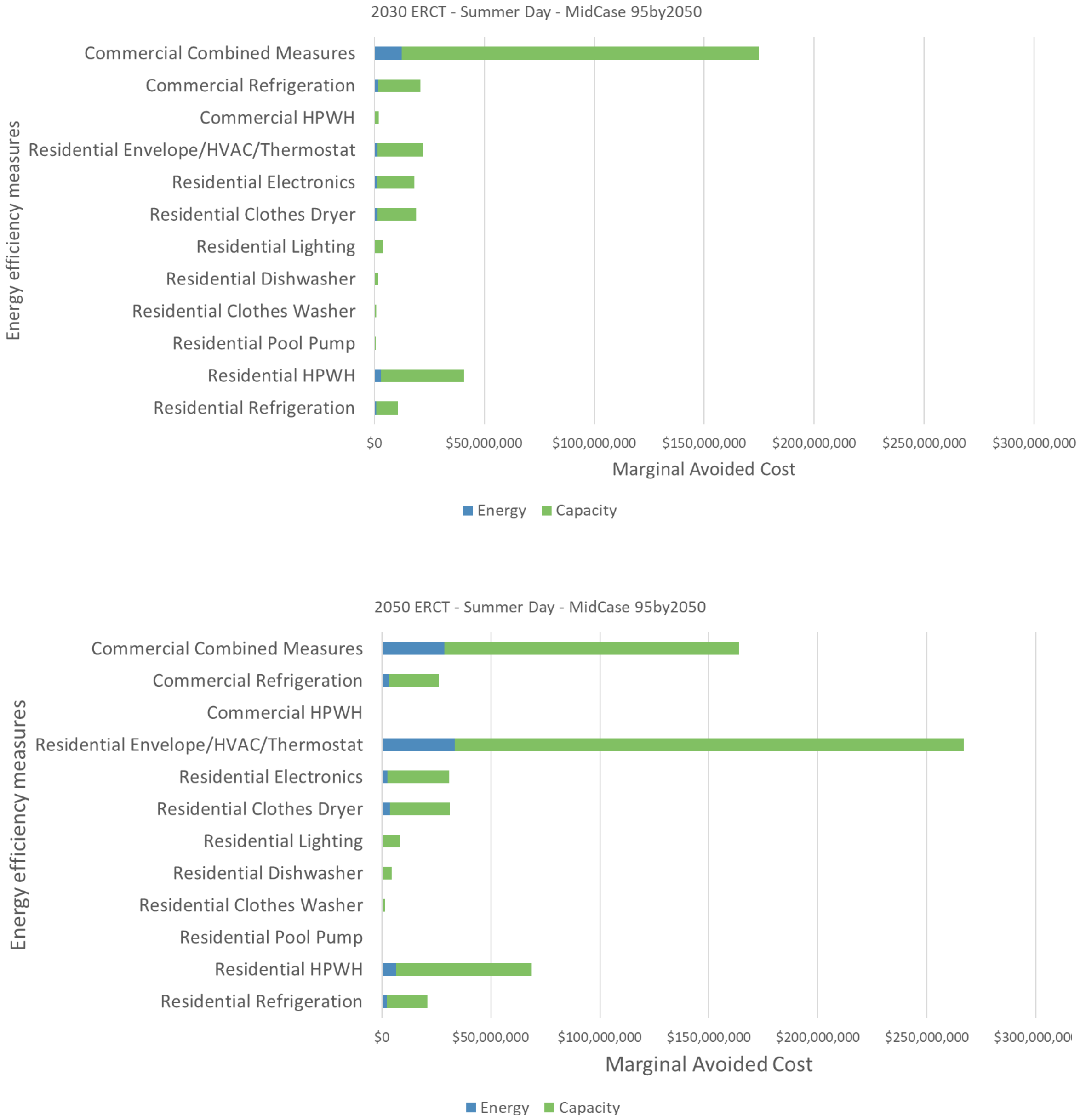


Figure B11. Summer peak day marginal avoided costs in Texas (ERCT) in the MidCase 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs are drawn from June 27 (2030) and June 26 (2050) within Cambium, while energy savings are both drawn from July 12 within Scout.

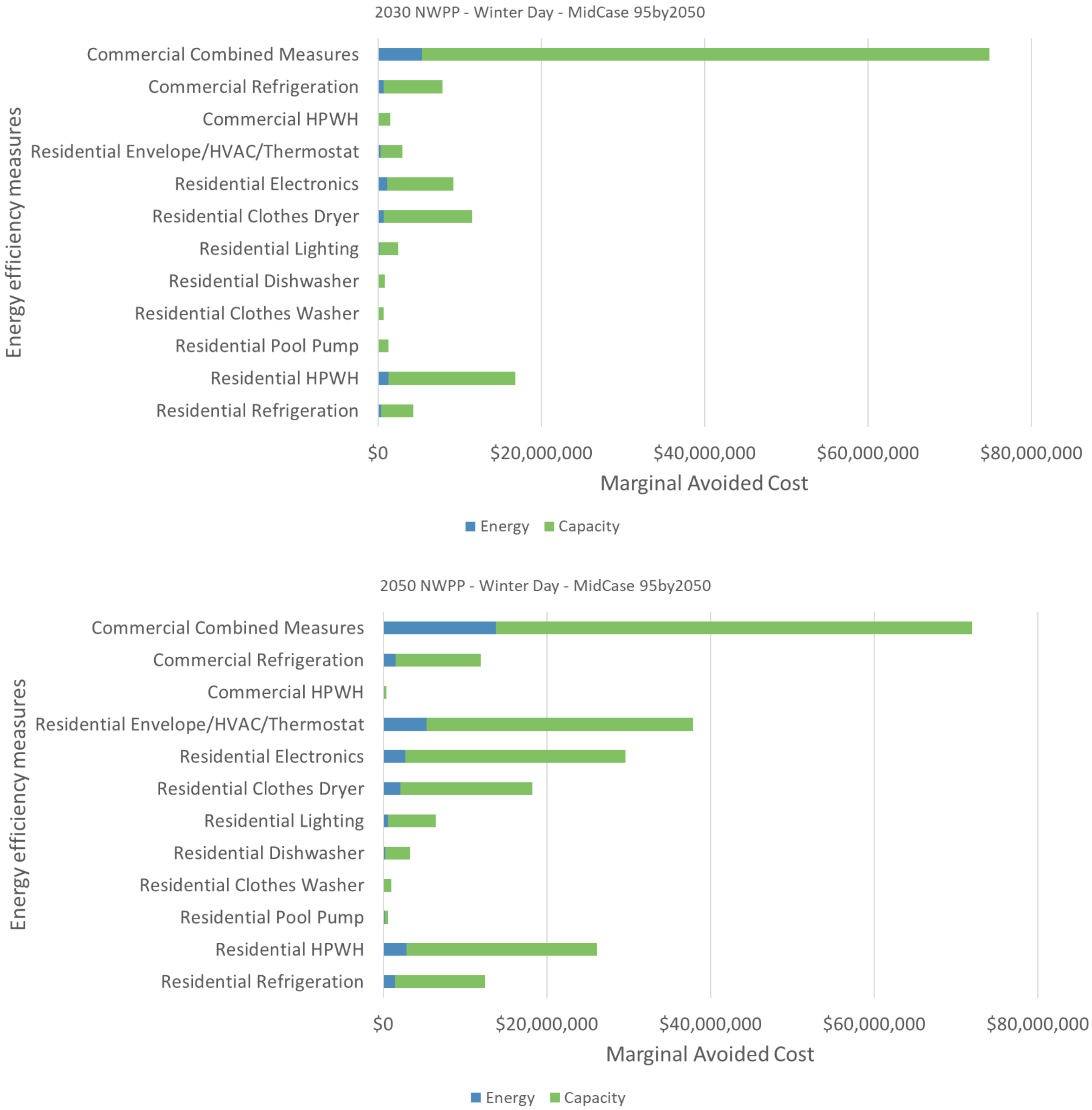
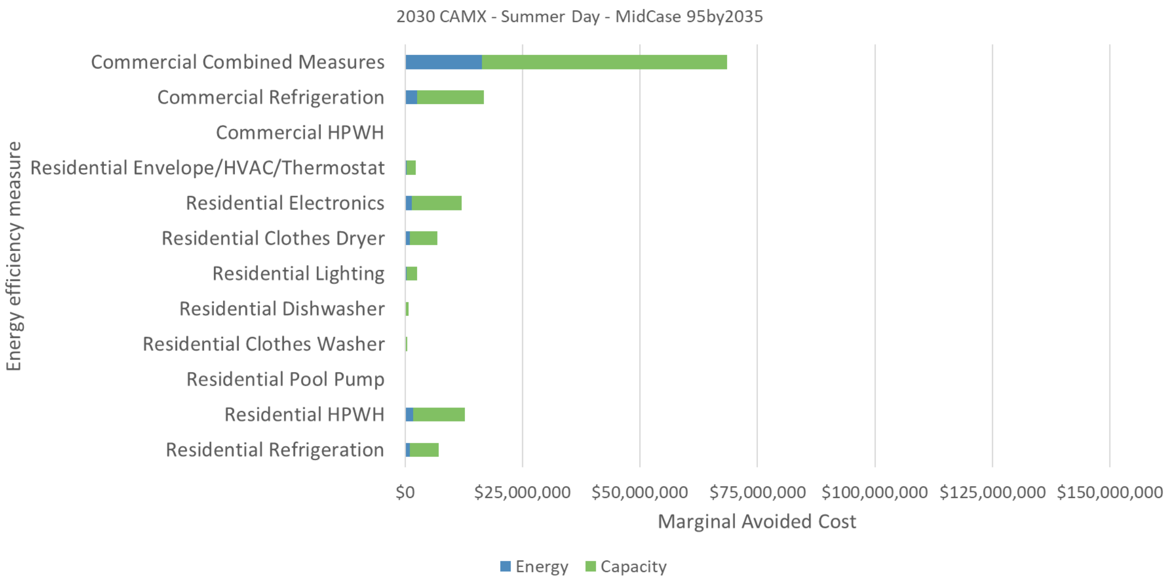


Figure B12. Winter peak day marginal avoided costs in the Northwest (NWPP) in the MidCase 95x2050 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs are drawn from January 13 (2030) and January 12 (2050) within Cambium, while energy savings are drawn from January 26 (2030) and December 29 (2050) within Scout.

Figures B13 through B17 contain representative peak day marginal avoided cost results for all regions under the 95x2035 scenario. As with the 95x2050 scenario, of the five regions studied in this report only the Northwest experiences peak day costs during the winter season.



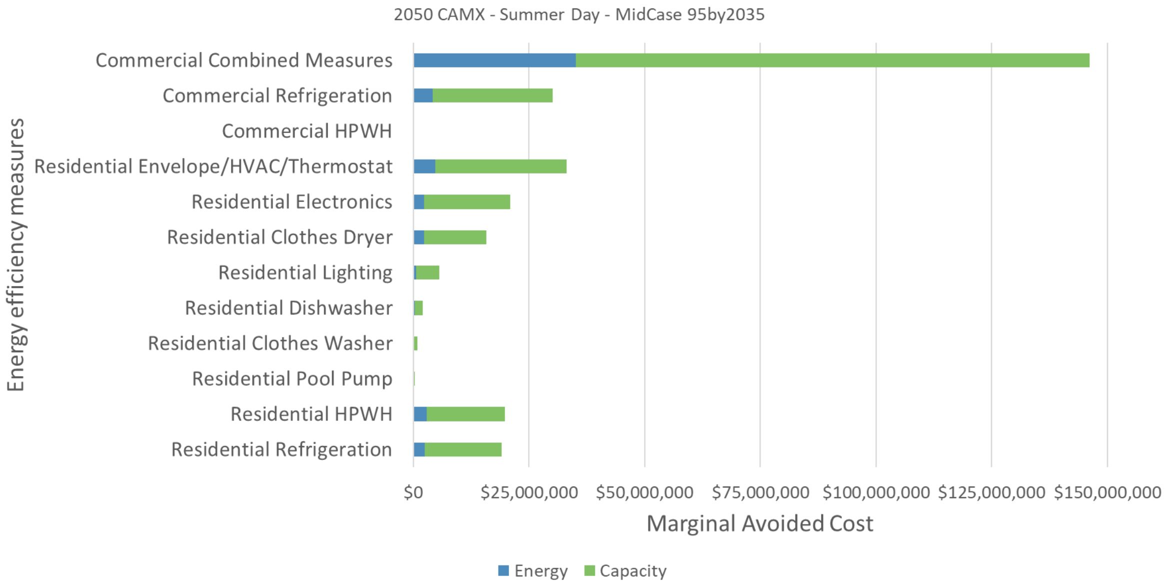


Figure B13. Summer peak day marginal avoided costs in California (CAMX) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs for both figures are drawn from August 14 within Cambium, while energy savings are both drawn from August 3 within Scout.

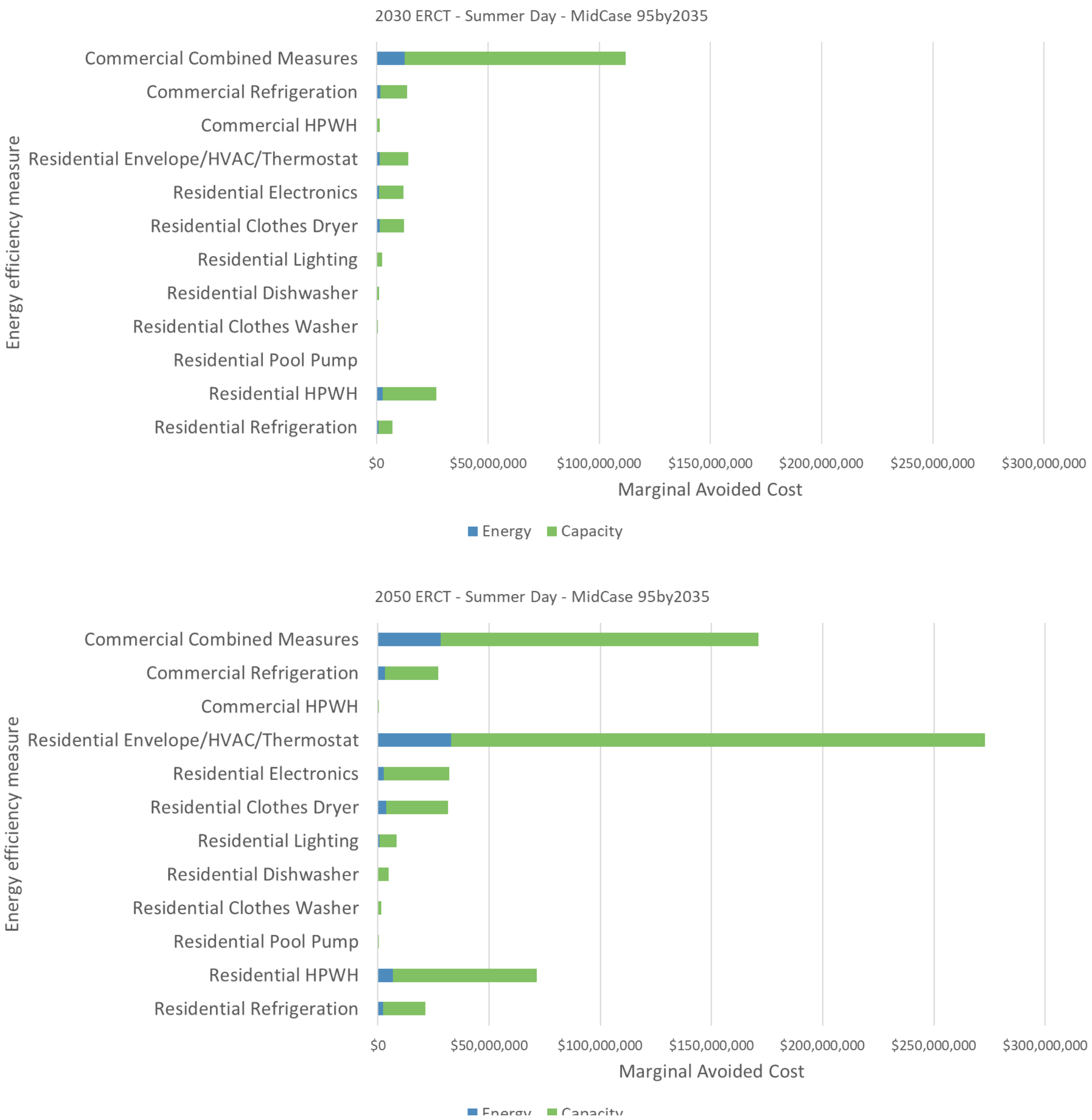
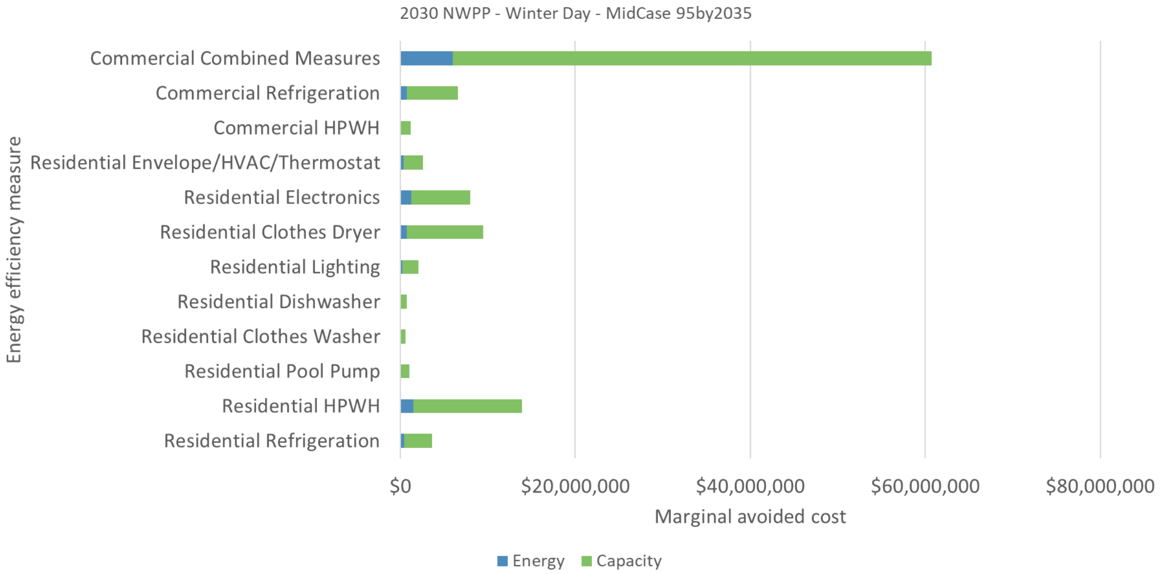


Figure B14. Summer peak day marginal avoided costs in Texas (ERCT) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs are drawn from June 27 (2030) and June 26 (2050) within Cambium, while energy savings are both drawn from July 12 within Scout.



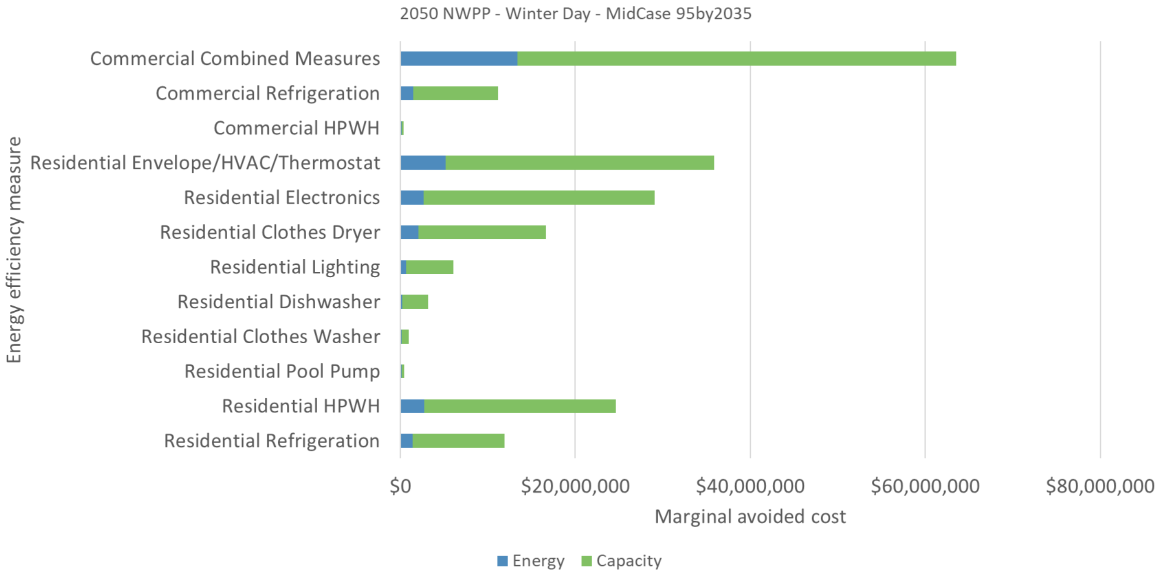
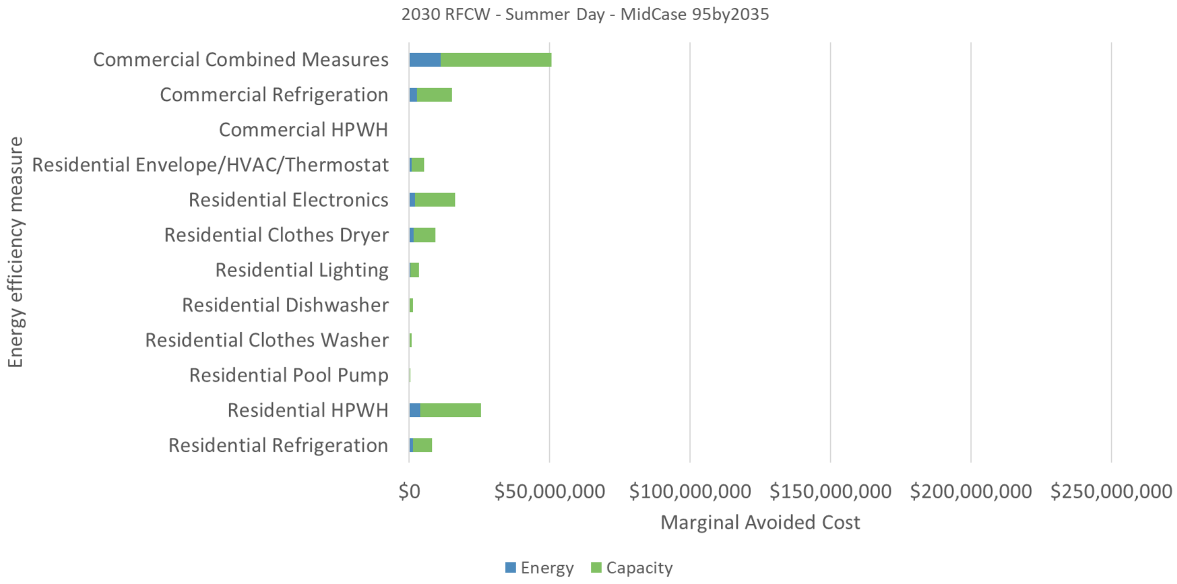


Figure B15. Winter peak day marginal avoided costs in the Northwest (NWPP) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs are drawn from January 13 (2030) and January 12 (2050) within Cambium, while energy savings are both drawn from January 26 (2030) and December 29 (2050) within Scout.



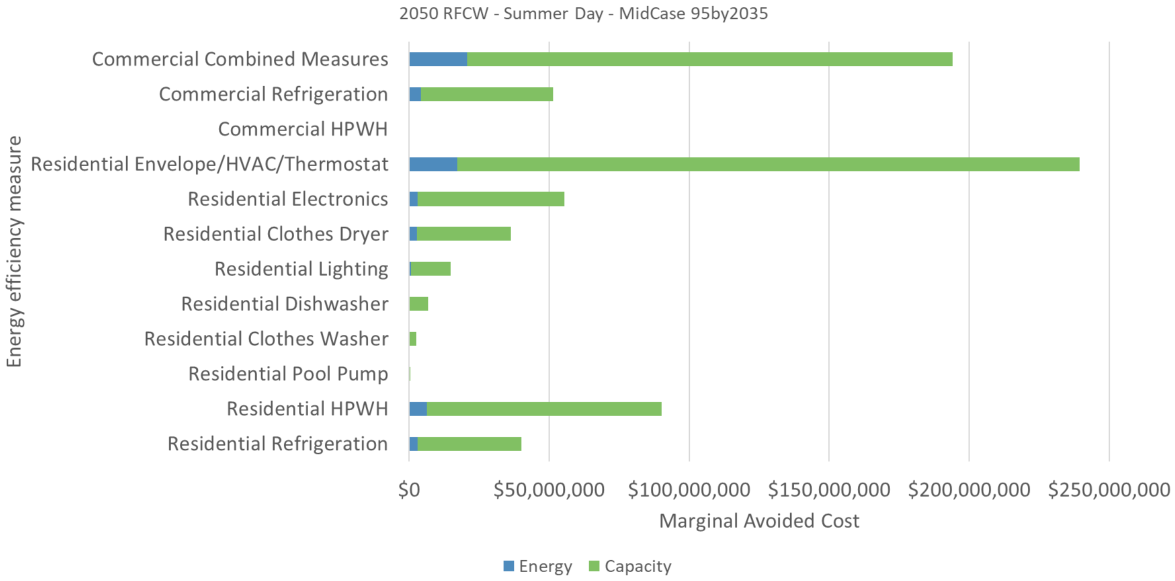


Figure B16. Summer peak day marginal avoided costs in the Midwest (RFCW) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs for both figures are drawn from July 7 within Cambium, while energy savings are both drawn from July 22 within Scout.

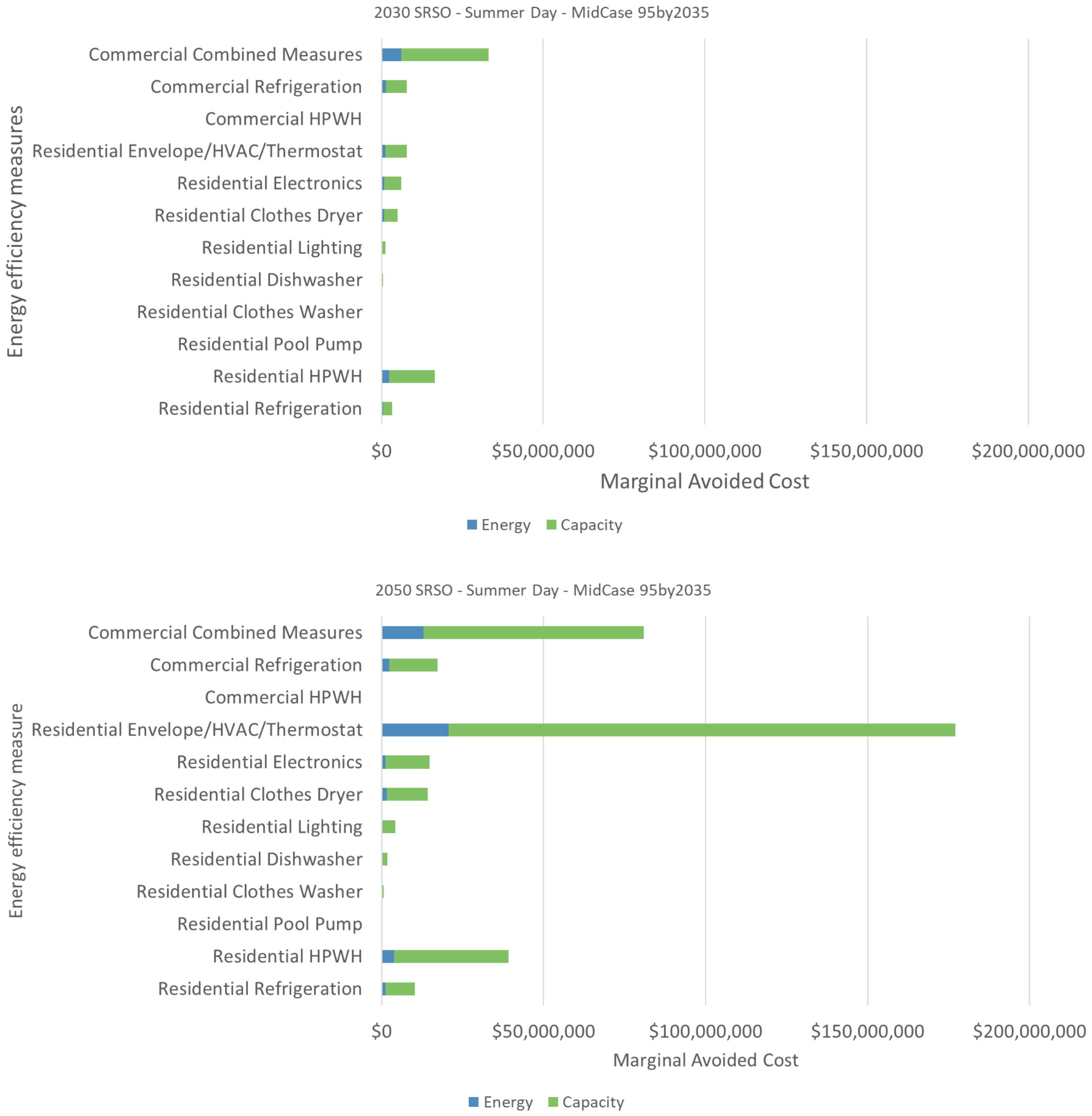


Figure B17. Summer peak day marginal avoided costs in the Southeast (SRSO) in the MidCase 95x2035 renewable energy scenario. Costs are presented by energy efficiency measure/package and disaggregated into their avoided energy and capacity costs. Results are presented in 2030 (top) and 2050 (bottom). Avoided costs for both figures are drawn from July 1 within Cambium, while energy savings are both drawn from July 8 within Scout.

We offer an additional perspective on energy efficiency's benefits during peak days in tables B5 through B8. These tables consider the avoided costs delivered by efficiency measures and packages for a single peak day in both the summer and winter seasons. To facilitate a more direct comparison with "commercial combined measures," we aggregate the following residential measures into "residential combined measures": clothes dryer, electronics, HVAC/envelope/thermostat, lighting, pool pump, clothes washer, and dishwasher. The tables below only contain the EE measures that contribute the largest percentage of total possible avoided electricity system costs for the given region, year, season, and renewable energy scenario.

Table B5. Energy efficiency measures and packages that deliver the greatest avoided electricity system costs during summer and winter peak days in 2030 for the 95x2050 renewable energy scenario

Region	Summer	Winter
CAMX	• Commercial Combined Measures ($77 million) • Residential Combined Measures ($52 million) • Commercial Refrigeration ($19 million) • Residential HPWH ($15 million)	• Commercial Combined Measures ($4.2 million) • Residential Combined Measures ($3.5 million)
ERCT	• Commercial Combined Measures ($175 million) • Residential Combined Measures ($67 million) • Residential HPWH ($41 million) • Commercial Refrigeration ($21 million)	• Commercial Combined Measures ($6.5 million) • Residential Combined Measures ($2.8 million)
NWPP	• Commercial Combined Measures ($6.4 million) • Residential Combined Measures ($3.0 million)	• Commercial Combined Measures ($75 million) • Residential Combined Measures ($29 million) o Clothes Dryer ($12 million) o Electronics ($9.2 million) • Residential HPWH ($17 million)
RFCW	• Commercial Combined Measures ($126 million) • Residential Combined Measures ($72 million) o Electronics ($29 million) • Residential HPWH ($52 million) • Commercial Refrigeration ($33 million)	• Commercial Combined Measures ($10 million) • Residential Combined Measures ($4 million)
SRSO	• Commercial Combined Measures ($17 million) • Residential Combined Measures ($13 million) • Residential HPWH ($10 million)	• Commercial Combined Measures ($4.7 million) • Residential Combined Measures ($2.8 million) • Residential HPWH ($2.7 million)

Table B6. Energy efficiency measures and packages that deliver the greatest avoided electricity system costs during summer and winter peak days in 2050 for the 95x2050 renewable energy scenario

Region	Summer	Winter
CAMX	• Commercial Combined Measures ($43 million) • Residential Combined Measures ($40 million) • Commercial Refrigeration ($18 million)	• Commercial Combined Measures ($22 million) • Residential Combined Measures ($17 million) o Envelope/HVAC/ICT ($10.5 million)
ERCT	• Residential Combined Measures ($343 million) o Envelope/HVAC/ICT ($264 million) • Commercial Combined Measures ($164 million) • Residential HPWH ($69 million)	• Commercial Combined Measures ($18 million) • Residential Combined Measures ($17 million) o Envelope/HVAC/ICT ($10.0 million) • Residential HPWH ($7.9 million)
NWPP	• Residential Combined Measures ($102 million) o Envelope/HVAC/ICT ($77 million) • Commercial Combined Measures ($38 million) • Residential HPWH ($13 million)	• Residential Combined Measures ($97 million) o Envelope/HVAC/ICT ($38 million) o Electronics ($30 million) • Commercial Combined Measures ($72 million) • Residential HPWH ($26 million)
RFCW	• Residential Combined Measures ($384 million) o Envelope/HVAC/ICT ($261 million) o Electronics ($58 million) • Commercial Combined Measures ($213 million) • Residential HPWH ($96 million)	• Commercial Combined Measures ($49 million) • Residential Combined Measures ($45 million) o Envelope/HVAC/ICT ($30 million)
SRSO	• Residential Combined Measures ($207 million) o Envelope/HVAC/ICT ($173 million) • Commercial Combined Measures ($79 million) • Residential HPWH ($38 million)	• Residential Combined Measures ($80 million) o Envelope/HVAC/ICT ($69 million) • Commercial Combined Measures ($33 million) • Residential HPWH ($17 million)

Table B7. Energy efficiency measures and packages that deliver the greatest avoided electricity system costs during summer and winter peak days in 2030 for the 95x2035 renewable energy scenario

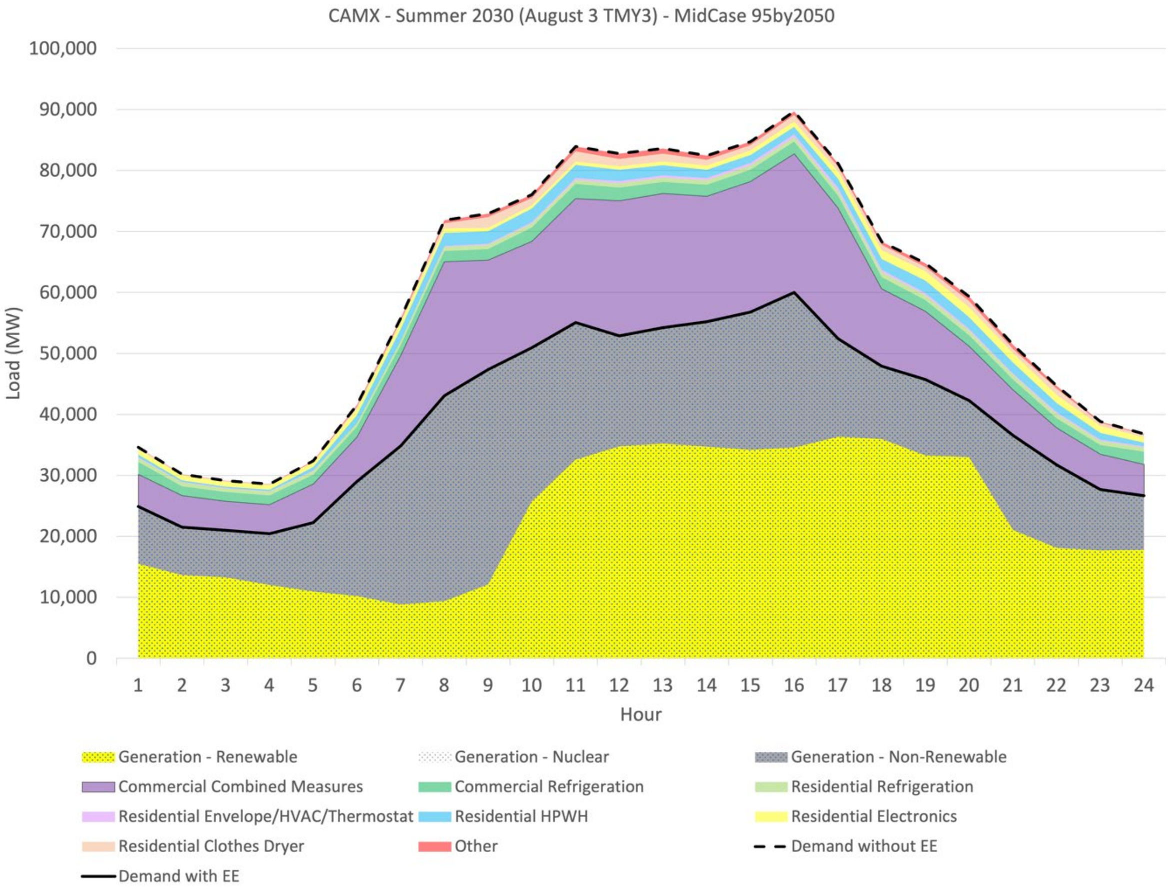
Region	Summer	Winter
CAMX	• Commercial Combined Measures ($69 million) • Residential Combined Measures ($25 million) • Commercial Refrigeration ($17 million) • Residential HPWH ($13 million)	• Commercial Combined Measures ($9.8 million) • Residential Combined Measures ($3.3 million)
ERCT	• Commercial Combined Measures ($112 million) • Residential Combined Measures ($43 million) • Residential HPWH ($27 million) • Commercial Refrigeration ($14 million)	• Commercial Combined Measures ($8.9 million) • Residential Combined Measures ($3.6 million)
NWPP	• Commercial Combined Measures ($20 million) • Residential Combined Measures ($11 million)	• Commercial Combined Measures ($55 million) • Residential Combined Measures ($24 million) o Clothes Dryer ($9 million) o Electronics ($7 million) • Residential HPWH (12 million)
RFCW	• Commercial Combined Measures ($51 million) • Residential Combined Measures ($37 million) o Electronics ($16 million) • Residential HPWH ($25 million) • Commercial Refrigeration ($15 million)	• Commercial Combined Measures ($10 million) • Residential Combined Measures ($4.2 million)
SRSO	• Commercial Combined Measures ($33 million) • Residential Combined Measures ($21 million) • Residential HPWH ($16 million)	• Commercial Combined Measures ($8.3 million) • Residential Combined Measures ($4.7 million) • Residential HPWH ($4.4 million)

Table B8. Energy efficiency measures and packages that deliver the greatest avoided electricity system costs during summer and winter peak days in 2050 for the 95x2035 renewable energy scenario

Region	Summer	Winter
CAMX	• Commercial Combined Measures ($146 million) • Residential Combined Measures ($79 million) o Envelope/HVAC/ICT ($33 million) o Electronics ($21 million) o Clothes Dryer ($16 million) • Commercial Refrigeration ($30 million) • Residential HPWH ($20 million) • Residential Refrigerator ($19 million)	• Commercial Combined Measures ($21 million) • Residential Combined Measures ($14 million) o Envelope/HVAC/ICT ($8.7 million)
ERCT	• Residential Combined Measures ($352 million) o Envelope/HVAC/ICT ($273 million) o Electronics ($32 million) o Clothes Dryer ($32 million) • Commercial Combined Measures ($171 million) • Residential HPWH ($72 million) • Commercial Refrigeration ($27 million)	• Residential Combined Measures ($71 million) o Envelope/HVAC/ICT ($27 million) o Electronics ($21 million) • Commercial Combined Measures ($69 million) • Residential HPWH ($45 million)
NWPP	• Commercial Combined Measures ($26 million) • Residential Combined Measures ($22 million) o Envelope/HVAC/ICT ($12 million) • Residential HPWH ($5 million)	• Residential Combined Measures ($92 million) o Envelope/HVAC/ICT ($36 million) o Electronics ($29 million) o Clothes Dryer ($17 million) • Commercial Combined Measures ($64 million) • Residential HPWH ($25 million)
RFCW	• Residential Combined Measures ($356 million) o Envelope/HVAC/ICT ($239 million) o Electronics ($56 million)	• Commercial Combined Measures ($50 million) • Residential Combined Measures ($46 million) o Envelope/HVAC/ICT ($31 million)

Region	Summer	Winter
	o Clothes Dryer ($36 million) • Commercial Combined Measures ($194 million) • Residential HPWH ($90 million) • Commercial Refrigeration ($52 million) • Residential Refrigeration ($40 million)	• Residential HPWH ($8 million)
SRSO	• Residential Combined Measures ($213 million) o Envelope/HVAC/ICT ($177 million) • Commercial Combined Measures ($81 million) • Residential HPWH ($39 million)	• Residential Combined Measures ($86 million) o Envelope/HVAC/ICT ($74 million) • Commercial Combined Measures ($35 million) • Residential HPWH ($18 million)

Figures B18 through B21 contain additional load savings and generation profiles during peak net load days in California, the Northwest, the Midwest, and the Southeast under the 95x2050 scenario. Results for the 95x2035 scenario (not included) are similar to those for the 95x2050 scenario and are available upon request.


CAMX - Summer 2030 (August 3 TMY3) - MidCase 95by2050
Load (MW)
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24
Hour
Generation - Renewable
Generation - Nuclear
Generation - Non-Renewable
Commercial Combined Measures
Commercial Refrigeration
Residential Refrigeration
Residential Envelope/HVAC/Thermostat
Residential HPWH
Residential Electronics
Residential Clothes Dryer
Other
Demand without EE
Demand with EE

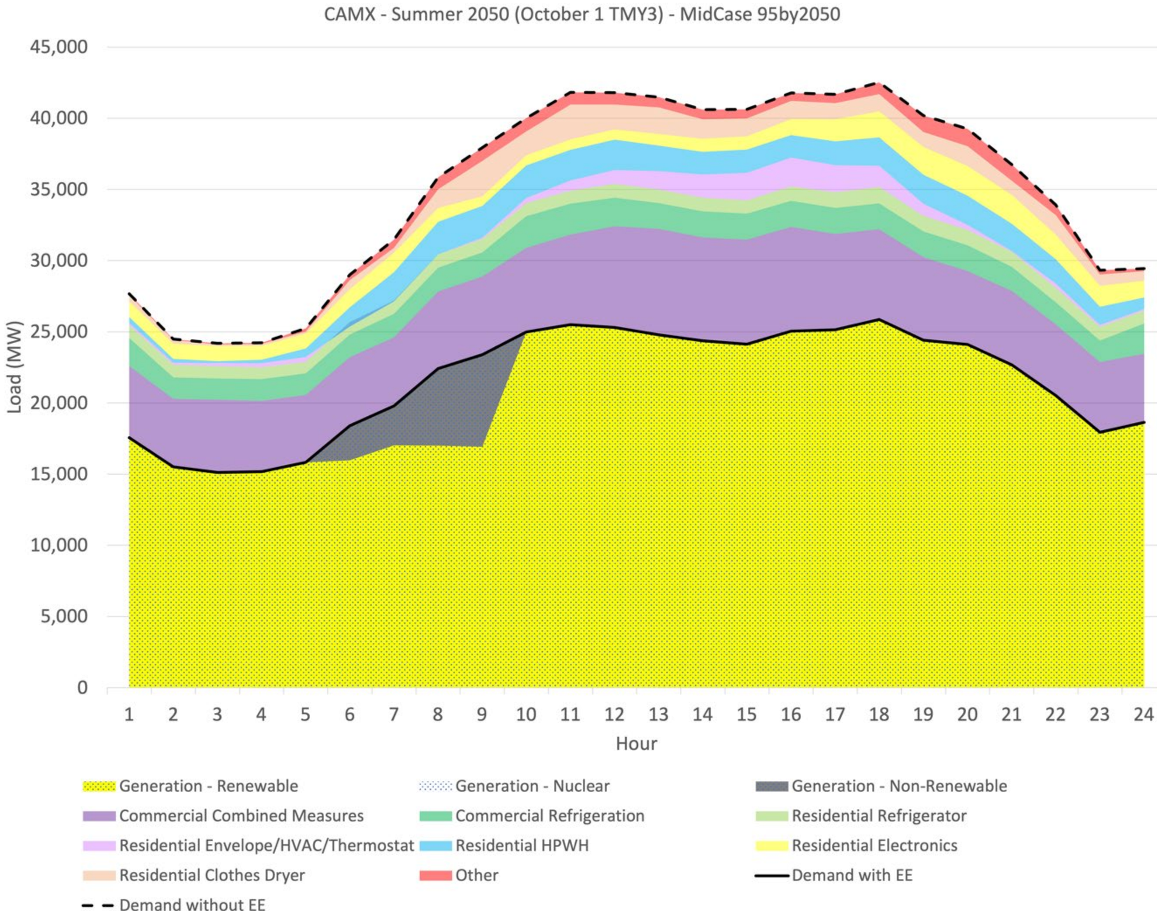
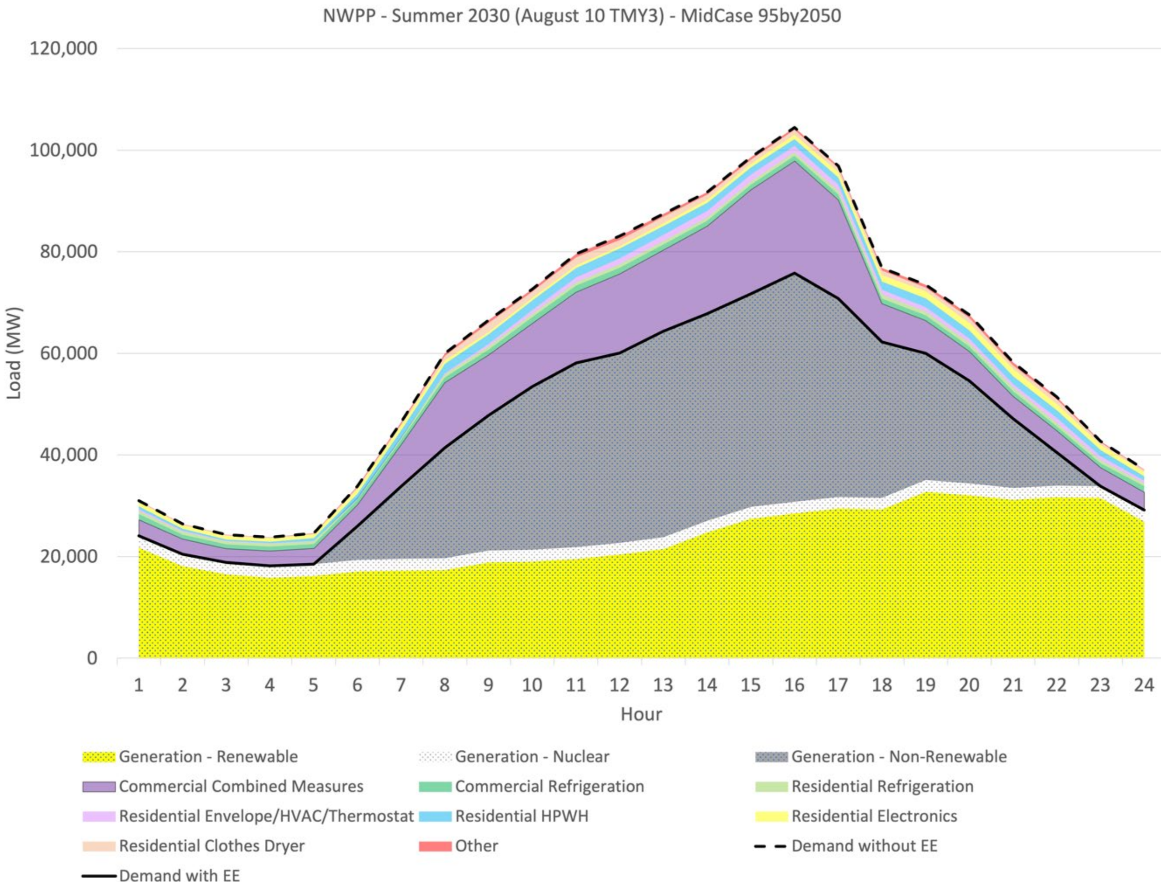


Figure B18. Load reduction potential of energy efficiency measures during peak net load days of August 14 (2030, top) and October 2 (2050, bottom) in California (CAMX) under the 95x2050 scenario


NWPP - Summer 2030 (August 10 TMY3) - MidCase 95by2050
Load (MW)
120,000
100,000
80,000
60,000
40,000
20,000
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Hour
Generation - Renewable
Generation - Nuclear
Generation - Non-Renewable
Commercial Combined Measures
Commercial Refrigeration
Residential Refrigeration
Residential Envelope/HVAC/Thermostat
Residential HPWH
Residential Electronics
Residential Clothes Dryer
Other
Demand without EE
Demand with EE

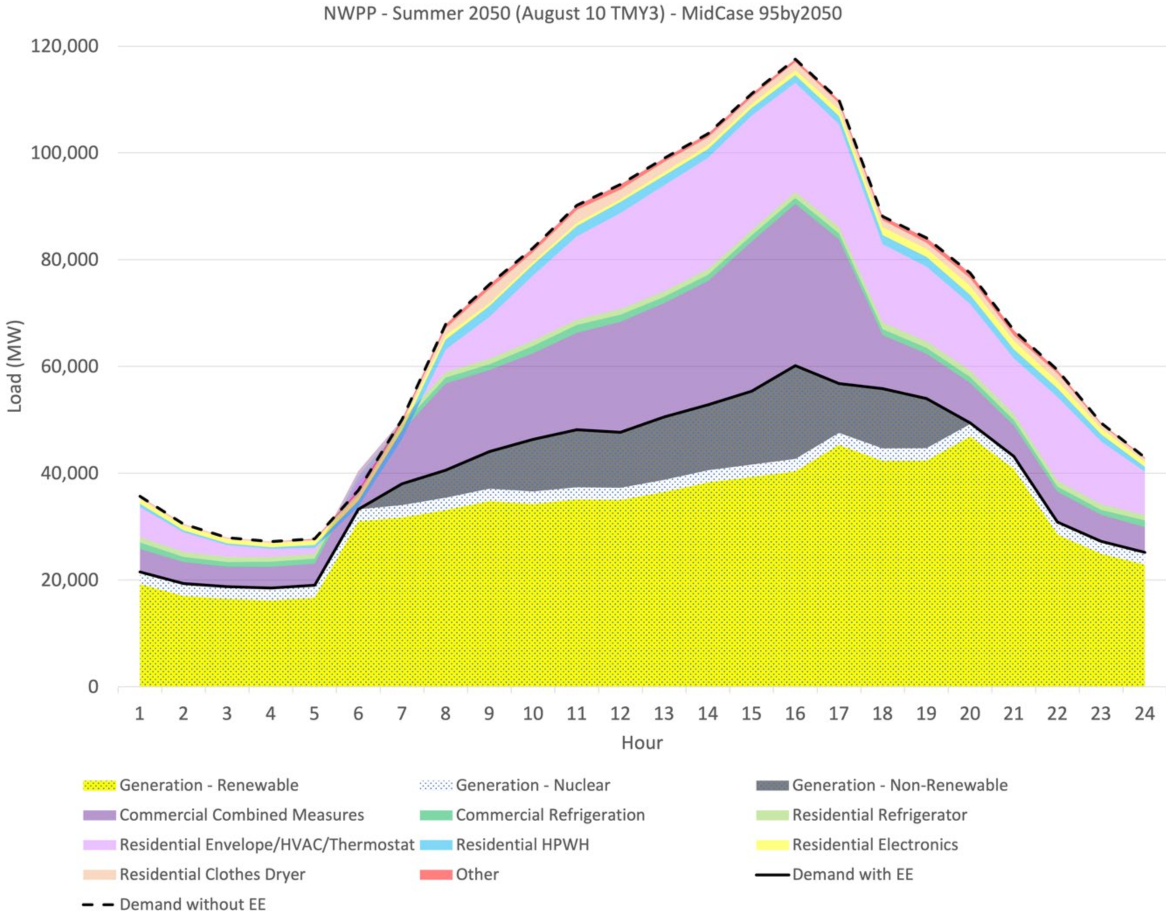
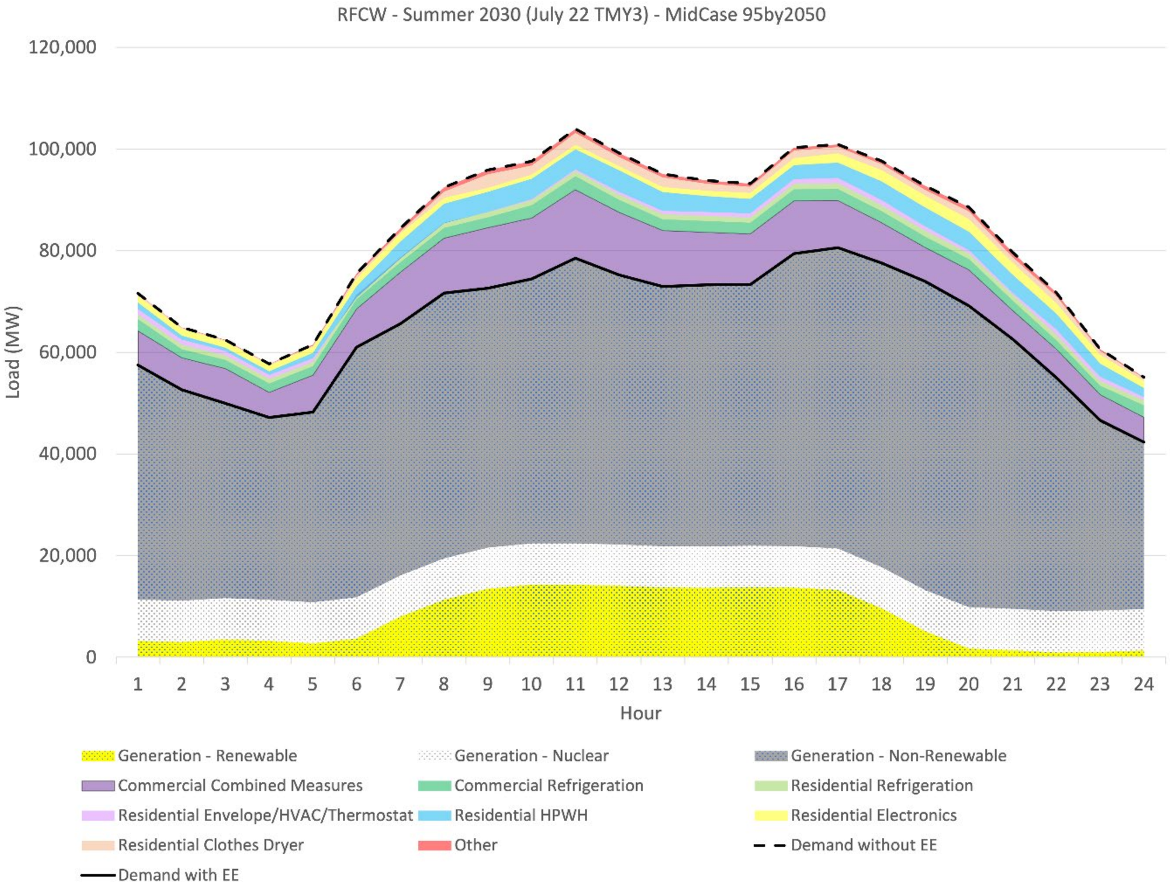


Figure B19. Load reduction potential of energy efficiency measures during peak net load day of August 17 in 2030 (top) and 2050 (bottom) in the Northwest (NWPP) under the 95x2050 scenario


RFCW - Summer 2030 (July 22 TMY3) - MidCase 95by2050
120,000
100,000
80,000
60,000
40,000
20,000
0
Load (MW)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Hour
Generation - Renewable
Generation - Nuclear
Generation - Non-Renewable
Commercial Combined Measures
Commercial Refrigeration
Residential Refrigeration
Residential Envelope/HVAC/Thermostat
Residential HPWH
Residential Electronics
Residential Clothes Dryer
Other
Demand without EE
Demand with EE

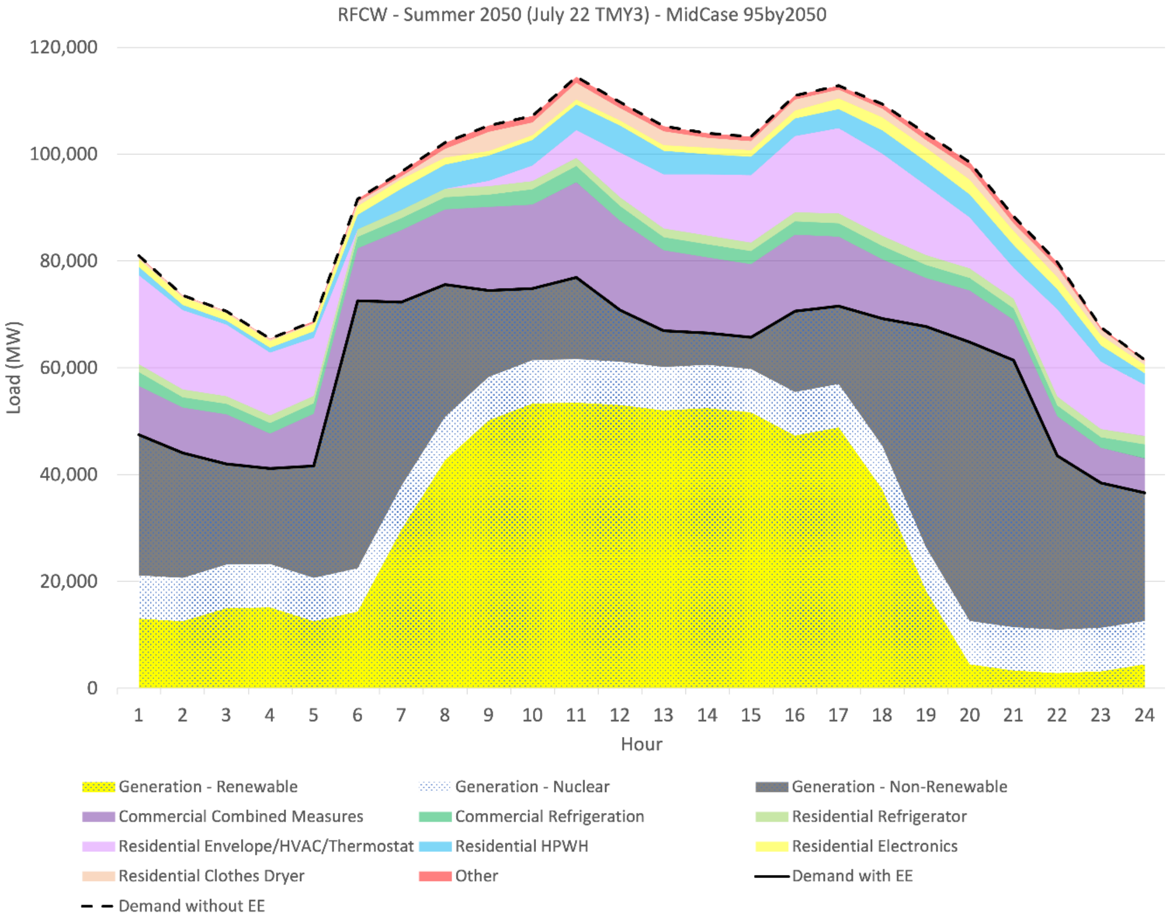
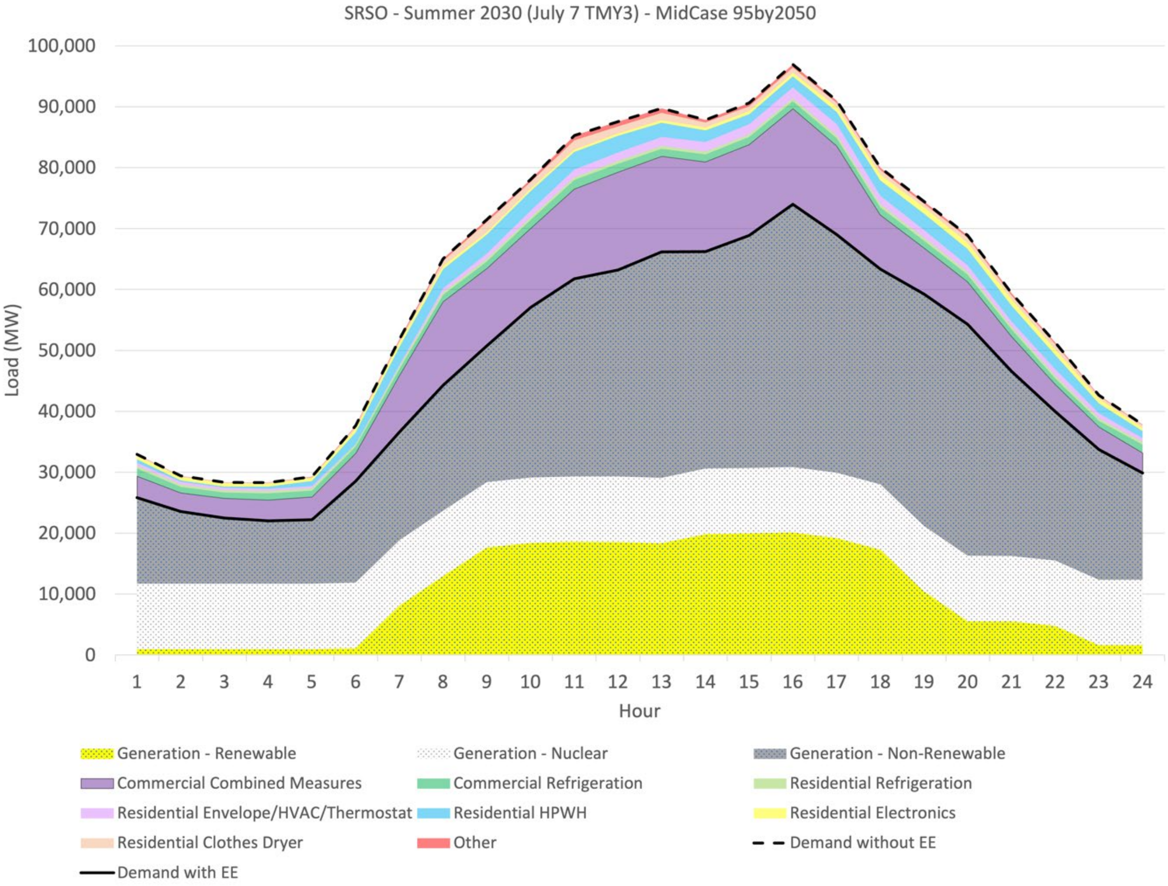


Figure B20. Load reduction potential of energy efficiency measures during peak net load day of July 7 in 2030 (top) and 2050 (bottom) in the Midwest (RFCW) under the 95x2050 scenario


SRSO - Summer 2030 (July 7 TMY3) - MidCase 95by2050
Load (MW)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Hour
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
Generation - Renewable
Generation - Nuclear
Generation - Non-Renewable
Commercial Combined Measures
Commercial Refrigeration
Residential Refrigeration
Residential Envelope/HVAC/Thermostat
Residential HPWH
Residential Electronics
Residential Clothes Dryer
Other
Demand without EE
Demand with EE

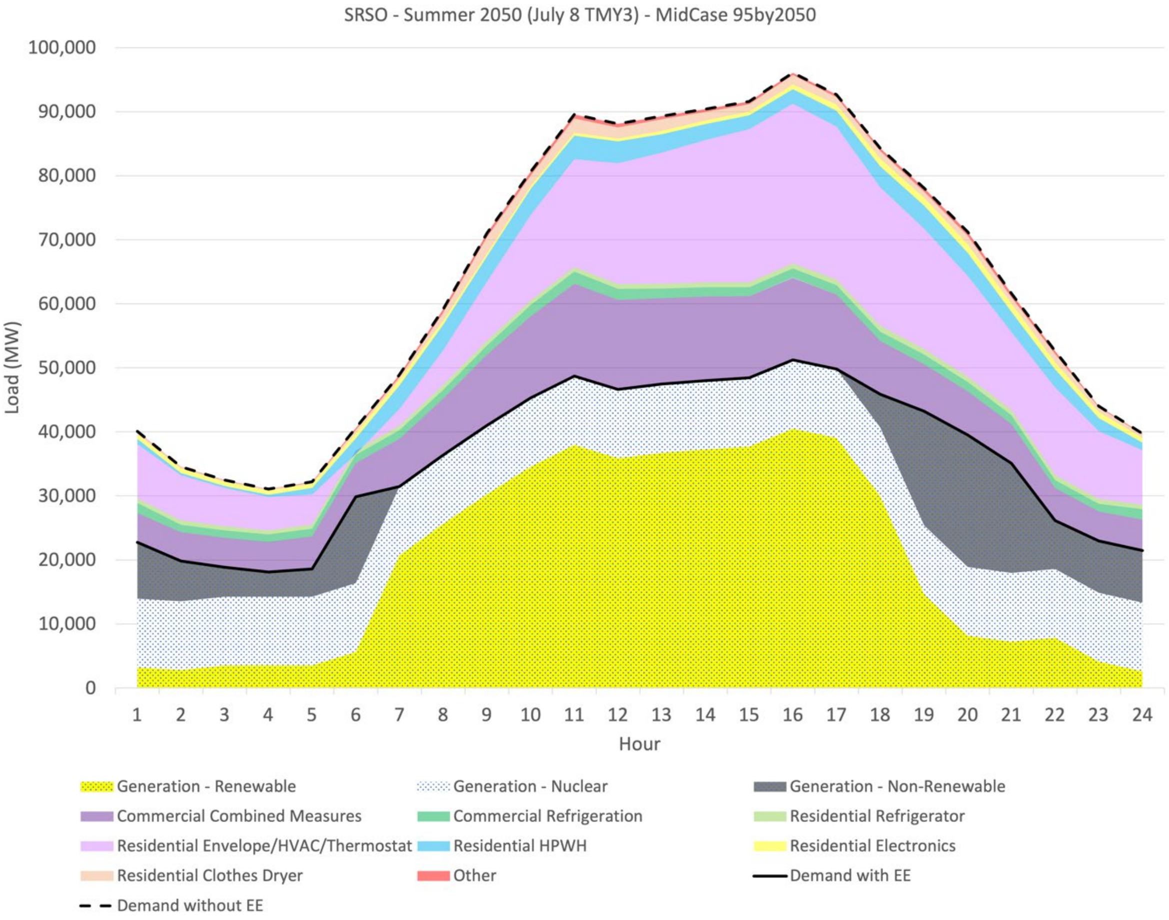


Figure B21. Load reduction potential of energy efficiency measures during peak net load days of June 30 (2030, top) and July 1 (2050, bottom) in the Southeast (SRSO) under the 95x2050 scenario

Finally, we present in figure B22 projected generation capacity requirements every two years through 2050 for the 95x2050 scenario with data collected from Cambium. Generation and generation capacity requirements for the 95x2035 scenario are presented in figures B23 and B24, respectively.

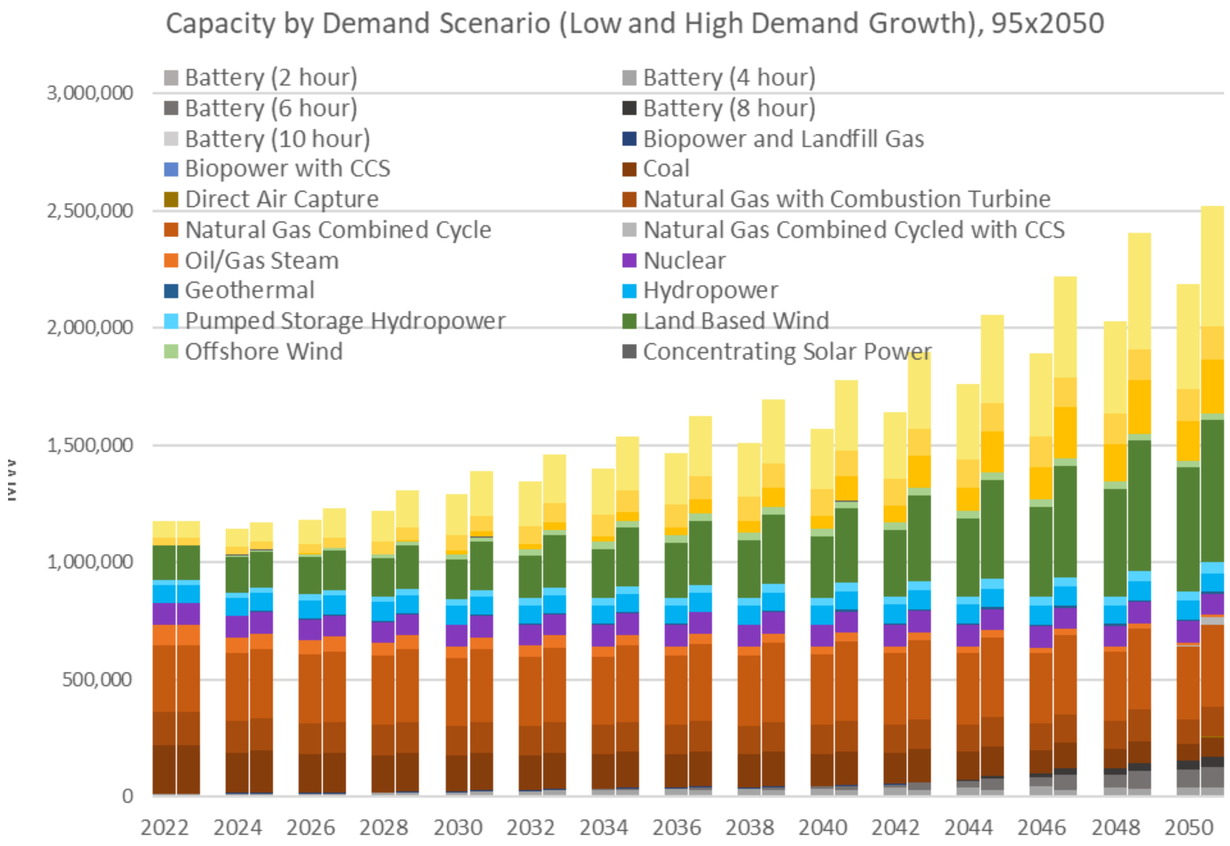


Figure B22. Projected U.S. generation capacity requirements for meeting a 95% decarbonized electricity by 2050 goal. Results are presented every two years with low demand (high efficiency) presented on the left and high demand (low efficiency) presented on the right. Data sourced from Cambium via the NREL Standard Scenarios.

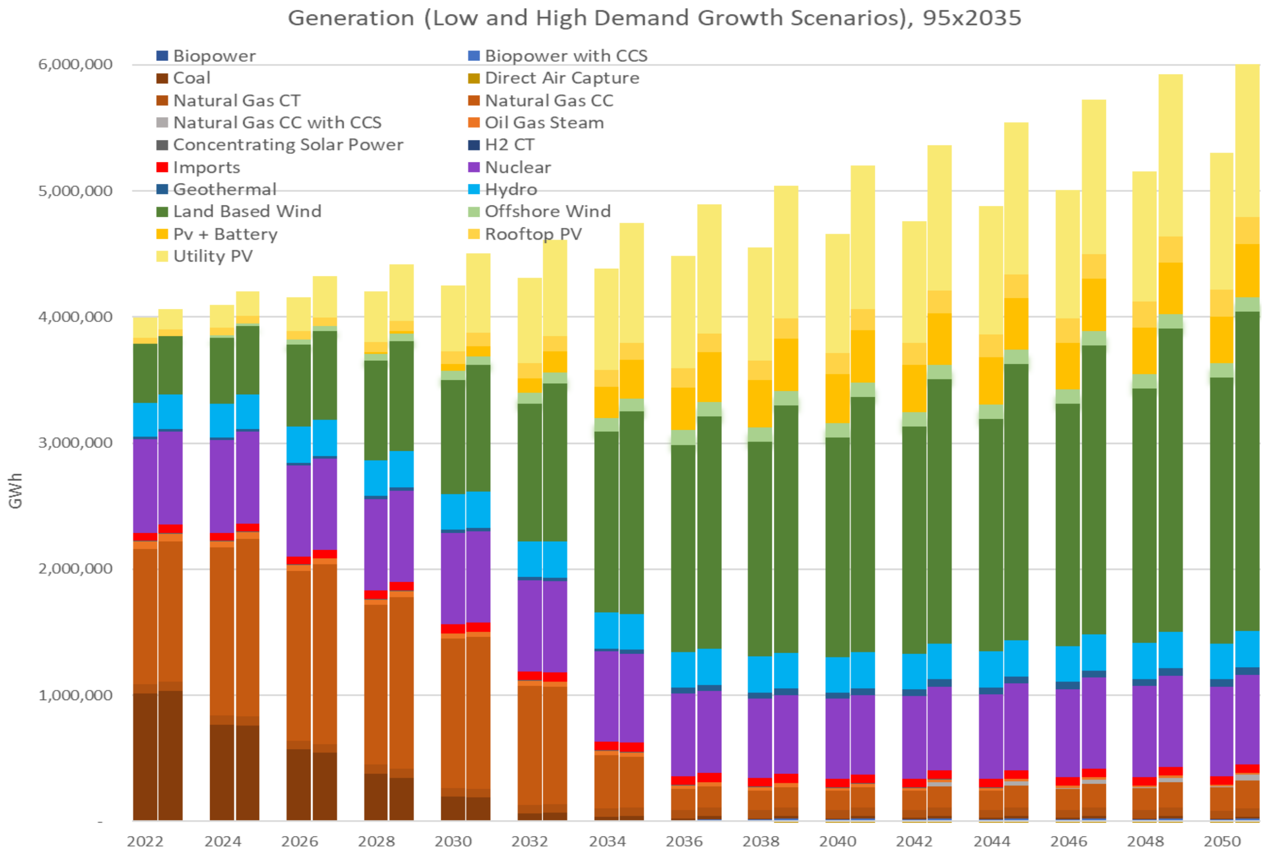


Figure B23. Projected U.S. generation requirements for meeting a 95% decarbonized electricity by 2035 goal. Results are presented every two years with low demand (high efficiency) presented on the left and high demand (low efficiency) presented on the right. Data sourced from Cambium via the NREL Standard Scenarios.

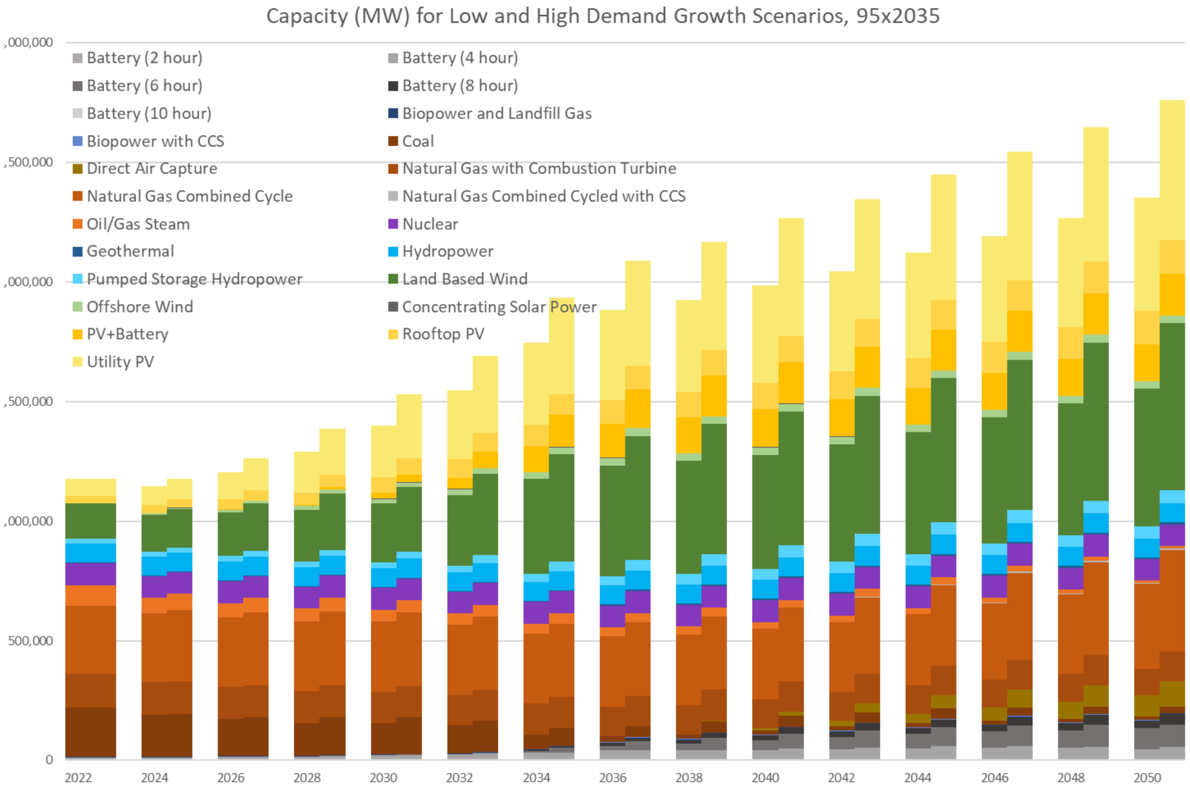


Figure B24. Projected U.S. generation capacity requirements for meeting a 95% decarbonized electricity by 2035 goal. Results are presented every two years with low demand (high efficiency) presented on the left and high demand (low efficiency) presented on the right. Data sourced from Cambium via the NREL Standard Scenarios