Efficiency and Demand Flexibility in Large Office Buildings

The Potential for Cost Savings and CO_2 Reductions from Lighting and Cooling Measures

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NOTICE

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Abstract

This report presents the estimated impact of implementing lighting and cooling efficiency and demand flexibility measures in large office buildings in each state in the contiguous United States. It estimates savings across three different metrics: bill savings, regional bulk power costs savings, and carbon dioxide (CO_2) emissions reductions.

The savings are based on a pre-existing modeled dataset that implements the efficiency and demand flexibility measures in order to reduce regional system peak load. This mimics the building load reduction that may occur when building managers react to utility signals for load reductions, which are timed to reduce system peaks. Note that regional system peaks are not necessarily coincident with peak building loads, peak electricity rates, or peak CO_2 emissions. Hence, the load reductions as estimated in this study do not optimize building load reductions or maximize savings for the three metrics reported.

Lighting efficiency and demand flexibility are estimated to reduce peak load 10–52 kW in a single large office building. Lighting load reductions result in customer bill savings of up to $8,800/yr per building, with the highest savings in southern and midwestern states, due to alignment between the peak periods and building loads in these regions, as defined in the study. Bulk power cost savings[1] are estimated at up to $3,240/yr/building, with greatest benefit in southern and northeastern states. CO_2 emissions reduction potential is highest in the Dakotas, Nebraska, across the Midwest, in West Virginia, and in Mississippi (<48,200 kg/yr/building).

Cooling efficiency and load shedding is found to reduce peak load up to 84 kW in a single large office building, with the greastest reductions in Michigan, Wisconsin, Indiana, Ohio and West Virginia. In all cases, the specific rate structure is a significant determinant in actual bill savings, which are estimated to be up to $3,940/yr/building. Marginal bulk power cost savings (<$2,280/yr/building) and CO_2 emissions reductions (<9,500 kg/yr/building) are highest in the southern states.

Cooling efficiency combined with pre-cooling (as a load shifting measure) is found to reduce building peak load up to 84 kW in the best case, but increase building peak load in many regions. In the northwest, this combination increased peak load in a single large office by 36 kW. This is because the measures, as modeled for this study[2], reduce regional system peak load, which is not necessarily coincident with building peak load. Despite peak load increases, bill savings are realized in many cases. Bill savings from cooling efficiency and pre-cooling, which are driven by the applicable utility rate tariff, are found to be greatest in Maine and the southern region of the country (<$3,040/yr/building). Bulk power cost savings (<$1,620/yr/building) and CO_2 emission reductions (<6,600 kg/yr/building) were highest in the South. However, because the measures, as modeled for this study, are not specifically configured to reduce load during high bulk power cost or high CO_2 emission periods, the pre-cooling measure combination is found to increase bulk power costs and CO_2 emissions in many states.

[1] Bulk power costs are estimates of the costs incurred by the bulk power system by marginal consumption. They are not estimates of retail electricity prices and they do not include all the costs of building and operating the electric system. See the Cambium model documentation (Gagnon et al. 2021) for a complete description of what is included in this metric.

[2] This study employs previously modeled data of the impact of efficiency and demand flexibility measures on building load. The model deployed measures to reduce regional system peak load. This mimics the load reduction effect that could result from responses to utility signals for load reductions. The timing of those load reductions are not necessarily coincident with peak building loads, peak electricity rates, or peak CO_2 emissions.

To realize the full potential for bill savings through an energy measure, building operators must identify how the measure will change the building load pattern and the interaction of this load change with the applicable rate tariff. To realize CO_2 emissions reductions, industry and state coordination can help incentivize increased consumption during periods of low-CO_2 emission hours while reducing load during high-CO_2 emissions hours. This could be accomplished through more explicit means such as forecasted marginal emission rates or through more indirect means such as retail tariff elements that reward consumption during high variable renewable energy generation periods.

Regular updates to data sets and analyses are critical. Regulators and policymakers are well positioned to facilitate the necessary coordination between the electric industry and building energy managers to develop appropriate price signals and incentives.

Acknowledgments

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Acronyms and Abbreviations

CO_2	carbon dioxide
COP	coefficient of performance
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EMM	Energy Market Module
GSA	General Services Administration
GTA	global temperature adjustment
LED	light-emitting diode
NREL	National Renewable Energy Laboratory
ReEDS	Regional Energy Deployment System
REopt	Renewable Energy Integration and Optimization

Definitions

Demand flexibility: Any modification (reduction or shift) in a customer's load that is not explicitly a result of an energy-efficiency or energy generation technology (e.g. modifications using distributed energy resources). The terms *energy flexibility* and *load flexibility* are often used interchangeably with *demand flexibility*. In this report, *demand flexibility* refers to both load-shedding and load-shifting measures.

Demand-side management: The modification of energy demand by customers through strategies, including energy efficiency, demand response, distributed generation, energy storage, electric vehicles, and/or time-of-use pricing structures.

Demand response: The change in the rate of electricity consumption in response to price signals or specific requests from a grid operator. Demand response is related to demand flexibility, but it is not explicitly mentioned in this report. Buildings can also shed and shift load outside of utility demand response calls, typically to reduce costs.

Energy efficiency: Ongoing reductions in energy use resulting from technology additions or retrofits that provide the same or an improved level of function.

Grid-interactive efficient building: Energy-efficient buildings that use smart technologies or otherwise actively manage load or distributed energy resources, such as solar photovoltaics and energy storage, to optimize energy use in a continuous and integrated way.

Load profile: A building's load profile describes how much energy the building is consuming during each unit of time (e.g. energy use during each hour of a year). (The term is typically used to refer to electricity consumption, but it can also describe on-site fuel use.) The terms *load shape* and *load curve* are often used interchangeably with *load profile*, but all refer to the timing of energy use.

Load shedding: The regular reduction in load within a set time period induced by the customer (either manually or on an automated basis) through a particular measure as opposed to in response to a utility call for load reduction. In this report, the term refers to cooling demand flexibility measures that result in regular load reductions that are not offset by increased demand in other periods.

Load shifting: The regular shifting of load from one set time period to another by the customer (either manually or on an automated basis) through a particular measure. In this report, the term refers to cooling demand flexibility measures that result in regular load reductions that are offset by increased demand in other periods.

Long-run marginal grid conditions: Both the short-run marginal grid conditions determined by the operation of an existing generation fleet as well as the longer-term changes caused by investment and retirement decisions. When a building persistently modifies its load over a sufficiently long time period to influence structural changes to the power system, the long-run marginal grid conditions determine the building's impact on the broader power system. In this study, long-run marginal grid conditions are used to determine the impact of energy-efficiency and demand flexibility investments on emissions reductions and capacity expansion costs. The combined energy and capacity costs are referred to as "bulk power costs" in this study.

Short-run marginal grid conditions: The characteristics of the generator dispatched to meet a marginal increase in electricity demand. When a building modifies its load, the short-run marginal grid conditions determine the impacts on the broader power system assuming a fixed set of grid assets. For instance, if a building reduces its demand in a given hour, the marginal generator accordingly reduces its output, which reduces the costs and emissions associated with operating the marginal generator. In this study, short-run marginal conditions are used to capture the impact of energy efficiency and demand flexibility on near-term bulk power costs, such as energy costs induced by burning fuel. The combined energy and capacity costs (which are calculated using long-run marginal grid conditions) are referred to as "bulk power costs" in this study.

Smart technologies for energy management: Advanced controls, sensors, models, and analytics used to manage distributed energy resources. Grid-interactive efficient buildings are characterized by their use of these technologies.

Contents

Figures

Tables

1.0 Background and Context

This report presents an analysis that was conducted at the request of state agency staff who are participating in the Grid-Interactive Efficient Building initiative working group funded by the Grid Modernization Laboratory Consortium. These working group members serve as energy and environmental policy advisors and program administrators across the United States. Discussions among them revealed a need for more granular (state-level) information about the potential for specific efficiency and demand flexibility measures in the built environment. The metrics of most interest to state decision makers were identified as: customer cost savings, utility system cost savings, and carbon dioxide (CO_2) emissions impacts.

The results of this research are anticipated to be particularly useful in state-level target formulation, regulatory design, and program and incentive development. The working group members deemed large office buildings to be of most interest for three reasons. First, state-level staff might already have connections to the large office building sector. Second, state-owned buildings have similar characteristics to large office buildings and thus can lead by example. Third, large office buildings might be well suited as subjects of incentive programs or targeted policies. The Energy Information Administration's Commercial Buildings Energy Consumption Survey indicates that, taken together, office buildings consume more electricity than other commercial building types (EIA, 2022). As such, this report aims to provide state-level estimates for the deployment of readily available technologies in large office buildings.

This work builds on other recent publications funded by the U.S. Department of Energy (DOE):

DOE's *National Roadmap for Grid-Interactive Efficient Buildings* (U.S. DOE, 2021) introduces opportunities to use efficiency, distributed generation, and demand flexibility to enable buildings to serve as clean, flexible resources that help reduce costs, improve comfort, and allow greater levels of renewable energy integration. It contains a set of references to support a variety of stakeholders. This report supports the concepts and recommendations presented in the roadmap by providing more detail on the potential to use individual efficiency and flexibility measures in large commercial buildings. DOE also published a series of technical reports highlighting the state of the art for specific grid-interactive building technologies.

U.S. Building Energy Efficiency and Flexibility as an Electric Grid Resource (Langevin, 2021) reports regional trends in electricity use and estimates the technical potential of a variety of building efficiency and flexibility measures to impact annual electricity use and net peak demand. The results of that study informed our decision to investigate lighting and cooling measures in this work. The authors found that lighting efficiency and peak period global temperature adjustments (GTA)—with and without precooling—are two measures that result in consistent peak demand reductions in large commercial buildings across the regions studied. Given those results, this study more closely investigates both lighting efficiency and peak period GTAs to better understand the potential of these measures in each U.S. state.

Assessing the Interactive Impacts of Energy Efficiency and Demand Response on Power System Costs and Emissions (Satchwell, 2022) explores the impact of ambitious efficiency and flexibility measures on the bulk power system at the system operator level and for the entire contiguous U.S. The study explores how the power system might change vis a vis dispatch and generation and transmission expansion as a result of efficiency and flexibility from buildings and seeks to answer questions potentially posed by utilities, regulators, and system operators. In contrast, this study takes a primarily building focused perspective, exploring how efficiency and flexibility can benefit individual building owners and occupants and the grid at the state level.

This study uses many of the same data sets[3] as other recent reports that focus on building grid interactivity, thus maintaining consistency and comparability. For example, the New Buildings Institute's GridOptimal Design Guidance provides fact sheets for a variety of building types and regions across the United States that draw on the same DOE Commercial Reference Buildings[4] and Cambium data set used in this analysis. This report differs in that it provides state-level detail, explores multiple metrics, and looks more closely at two high-impact strategies for a single building type.

The full set of results from this study are available in the National Renewable Energy Laboratory (NREL) Data Catalog.[5] In addition, the code used to calculate the results is available on GitHub.[6]

The DOE Office of Energy Efficiency and Renewable Energy Building Technologies Office has provided funding for Phase 2 of the work presented in this report, which will occur in fiscal years 2023 through 2025. Phase 2 will build on this effort to expand the results to additional building types and measures, better calibrate the operation of flexibility measures to realistic equipment responses, and develop measures with a flexible control framework that respond to a specific objective (e.g., bill savings, bulk power costs, or CO_2 emissions reductions) based on grid conditions.

2.0 Introduction

Electricity consumers across the residential, commercial, and industrial sectors are interested in opportunities to reduce their electricity bills and, increasingly, their carbon footprints. Simultaneously, utilities, system operators, and state decision makers are aiming to reduce costs, more effectively use existing grid assets, maintain power system reliability, and achieve CO_2 emissions reduction targets. At the intersection of the customer and utility perspectives, buildings and their associated loads offer opportunities to align the interests of consumers, system operators, and policymakers.

Increased interactivity between buildings and the broader electricity system is enabled by advancements in building control technologies, data availability, advanced metering, improved analytics for energy management, and new tariff designs. Collectively, these *smart technologies for energy management* are often referred to as grid-interactive efficient buildings. By shedding and shifting building load, these technologies and techniques can reduce electricity bills, emissions, and the cost of operating the grid—all while maintaining the comfort of building occupants.

In this study, we model the impact of lighting and cooling efficiency and demand flexibility measures in large office buildings in each state in the contiguous United States, and we present the results across three

[3] Building load profiles are derived from DOE Commercial Reference Buildings. Bill savings results draw on NREL's Utility Rate Database and Renewable Energy Integration and Optimization® (REopt®) tool. Bulk power costs and CO_2 emissions reductions rely on NREL's Cambium data set. For additional information on these data sets, see the Methodology and Appendices. DOE's End-Use Load Profile data set was not used for this modeling effort because it was not available at the onset of the project and because the data set explores only the *existing* building stock and does not easily allow for the exploration of energy-efficiency and demand flexibility upgrades.
[4] For more information on the Commercial Reference Buildings see Deru et al. (2011).
[5] The complete set of results organized by state is available for download at: https://data.nrel.gov/submissions/205.
[6] See: https://github.nrel.gov/tbowen/GEB_ECM_Impact_Estimator. The code for bill calculations resides within REopt and thus is not available through the GitHub repository.

different metrics: (1) customer bill savings, (2) avoided CO_2 emissions, and (3) electricity system operational cost savings.

Table 1 defines the measures as they were modeled. Although other measures might also be effectively applied in large office buildings, lighting and cooling efficiency upgrades and demand flexibility measures have several positive attributes: The technologies are readily available, the measures are relatively straightforward to implement, and they do not entail the compliance or action on the part of the building occupants that some measures require (e.g., plug-load measures). In addition, unlike heating load, cooling load is typically served by electricity, which allows us to simultaneously model the implementation of energy efficiency and demand flexibility of cooling measures and to explore the potential interplay among multiple measures. Table 2 indicates the summer and winter peak hours used for each region. These peak periods are based on seasonal grid conditions by Electricity Market Module (EMM) region and do not account for daily or sub-regional variations or utility tariffs.

Table 1: Definitions of Efficiency and Demand Flexibility Measures Studied in the Analysis

Measure	Definition[7]
Lighting energy efficiency	Lighting efficiency measures follow ASHRAE's Advanced Energy Design Guidelines. Lighting power density is reduced by an additional 15% from the base lighting schedule as a proxy for occupancy controls (per Advanced Energy Design Guidelines modeling guidance). Daylighting controls in the perimeter zones are set at 300 lux.[8]
Lighting demand flexibility	Lighting demand flexibility reduces lighting load during peak hours by 30% for occupied spaces and 60% for unoccupied spaces. Thresholds maintain safety (e.g., stairwells, hallways) and comfort for most occupants.
Cooling energy efficiency	Cooling energy-efficiency measures upgrade the existing water-cooled centrifugal chiller with 5.5 COP to a chiller of the same type with 7.0 coefficient of performance.
Cooling demand flexibility	Cooling demand flexibility refers to a GTA measure that adjusts zone temperatures during peak hours. In summer, the set point temperature increases from 75ºF to 80ºF GTA during the peak period, maintaining a comfort range from 73ºF–80ºF, based on ASHRAE Standard 55-2017. In winter, the set point temperature decreases from 70ºF to 68ºF GTA during the peak period, maintaining a comfort range from 68ºF–78ºF, based on ASHRAE Standard 55-2017.
Precooling	Precooling adjusts the zone cooling temperatures downward for the 4 hours preceding the peak period. (No preheating is assumed in winter because the risk of discomfort at 68ºF is low, particularly given that the peak period begins in the evening hours, when most commercial buildings have low occupancy.)

[7] These measures were defined in advance of this study and could not be modified. Future work will reconsider the design of these measures, including setpoint temperatures, precooling periods, and peak period definitions.

[8] The lighting measure captures changes in load due to changes in heating and cooling caused by switching to more efficient lighting fixtures. Inefficient lightbulbs (e.g., incandescent) generate heat as a byproduct of lighting, which increases cooling demand in the summer and decreases heating demand in the winter. When a large office building transitions to more efficient bulbs (e.g., LEDs) under the lighting energy-efficiency and demand response measure,

Table 2: Electricity System Peak Periods Used in the Modeling by Electricity Market Module (EMM) Region

EMM Region[a]	ASHRAE Climate Zone	Summer Peak Period (Daylight Savings Time)	Winter Peak Period (Local Standard Time)
FRCC	2A	6–9 p.m.	6–9 p.m.
AZNM	2B	6–9 p.m.	6–9 p.m.
SRVC	3A	8–11 p.m.	6–9 p.m.
SPSO	3A	7–10 p.m.	6–9 p.m.
ERCOT	3B	7–10 p.m.	8–11 p.m.
CAMX	3C	8–11 p.m.	6–9 p.m.
NYCW	4A	1–4 p.m.	5–8 p.m.
SPNO	4A	7–10 p.m.	6–9 p.m.
AZNM	4B	6–9 p.m.	6–9 p.m.
NWPP	4C	6–9 p.m.	6–9 p.m.
NYUP	5A	9 p.m.–12 a.m.	6–9 p.m.
RFCW	5A	3–6 p.m.	7–10 p.m.
RMPA	5B	6–9 p.m.	6–9 p.m.
NWPP	5C	6–9 p.m.	6–9 p.m.
MROW	6A	5–8 p.m.	7–10 p.m.
NEWE	6A	2–5 p.m.	6–9 p.m.
NWPP	6B	6–9 p.m.	6–9 p.m.
MROW	7	5–8 p.m.	7–10 p.m.

[a] A map and list of EMM region names is available in the Scout documentation website at https://scout-bto.readthedocs.io/en/stable/ecm_reference.html.

The following results provide estimates of the potential for using these lighting and cooling measures in a single large office building to reduce electricity bills, marginal bulk power costs, and CO_2 emissions. We also estimate the number of large office buildings in each state to provide an indication of statewide potential savings if the measures were implemented across all large office buildings in a state.

Building energy managers can use the building-level estimates as a guide when exploring options to reduce costs and CO_2 emissions in their buildings. For policymakers, this study can help inform the design of programs, incentives, or other regulatory actions to eliminate barriers to and to help incentivize technologies that show the most potential for achieving policy goals. Note that the ability of a measure to help achieve a particular goal is highly contingent on local conditions (local tariffs, local power system conditions, specific building load patterns) that can vary from the broad assumptions made in this study; therefore, when making investment or policy decisions, additional analysis should be conducted for the building(s) or region(s) of interest.

the reductions in summer cooling load are reflected in the final load savings. Increased heating demands in the winter, however, are not reflected because large office buildings are modeled using natural gas for heating.

3.0 Methodology

A range of tools and data sets is leveraged for this analysis:

- **Scout**: Provides an estimate for the impact of energy-efficiency and demand flexibility measures on a building's load profile for different prototype buildings at different geographic resolutions. This model relied on data at the EIA EMM region level, but results were also available at the climate zone level, and more recent versions provide results at the state-level, which was not available at the time of this report.[9]
- **Cambium**: Provides an estimate for the short-run and long-run marginal conditions (costs and emissions) of the power system at different geographic resolutions (e.g., at sub-state balancing areas all the way up to interconnection regions) and under different assumptions for future power system conditions.[10]
- **REopt**: Aids in the selection of appropriate retail tariffs for buildings in each location and calculates customer bills based on building load and tariff structures.[11]

The general workflow for the analysis is as follows:

1. Use Scout to develop a baseline and an efficient hourly load profile for each scenario. Each load profile represents the load of a single large office building in one state in the contiguous United States for a given year. We do not make assumptions about the level of adoption of the measures (that is, how many buildings would adopt the measures). The baseline profile represents the load from a current code-compliant building before a given energy-efficiency and/or demand flexibility measure(s) is deployed. The efficient profile represents the load after the measure(s) is deployed. The measures are deployed to reduce demand during regional peak periods. The regional peak periods are 4-hour windows specified for the summer and winter seasons, as detailed in Table 2. The change between the baseline and efficient load profiles reflects regional patterns in the electricity system load. The measures are not deployed in response to regionally specific cost or CO_2 profiles.
2. Use Cambium[12] to develop an hourly estimate for the change in short-run marginal bulk power cost[13](i.e., the costs that would be avoided by reducing demand in each hour)and the change in long-run marginal emissions (i.e., the emissions that would be avoided by reducing demand in each hour) for each state in the contiguous United States.
3. Align the (1) hourly load profiles and (2) marginal operating costs and emissions rates and take the product of the two to arrive at an hourly estimate for the cost and emissions savings for large office buildings across the United States. The sum of these hourly impacts provides an estimate of the annual impacts on the power system of implementing the measures in the building(s).

[9] For more information on the Scout model, see: https://scout.energy.gov/, https://scout-bto.readthedocs.io and Langevin et al. (2021).
[10] For more information on the Cambium model, see the model documentation in Gagnon et al. (2021).
[11] For more information on the REopt model, see the model documentation in Cutler et al. (2017).
[12] This analysis used the 2020 version of the Cambium model and relied on data for the year 2022 to produce total marginal bulk power cost results. For the emissions rates, a levelized value across a 15 year lifetime was used assuming a 6.4% discount rate.
[13] These costs are estimates of the costs incurred by the bulk power system by marginal consumption. They are not estimates of retail electricity prices and they do not include all the costs of building and operating the electric system. See Cambium model documentation for a full description of the metrics.

4. Identify the utility rates that are applicable to large office buildings in each region of study.[14] Pass the hourly load profiles (both "baseline" and "efficient" scenarios) to the REopt model to develop monthly bill estimates both before and after the measures are deployed. Compare the bills to develop an estimate of the annual customer savings from deploying the measure(s).

Due to the methodology employed, the results of this study might underestimate the potential cost and CO_2 savings because:

- The energy-efficiency and demand flexibility measures were not optimized to reduce customer bills. Intelligent automation controls and customer responses could take advantage of retail tariff elements (e.g., time-of-use peak and off-peak periods) to reduce customer bills even further than indicated by this study.
- The measures were not optimized to be reactive to local grid conditions (bulk power costs or CO_2 emissions). Improving the reactivity of measures to specific metrics is a goal for Phase 2 of the study. See Appendix A.3 for more detail on how measures are deployed.
- Energy-efficiency and demand flexibility measures can be used to address costs that are not represented in the Cambium data. Costs captured in the Cambium data include energy, capacity, and policy costs. There are additional costs, such as congestion on local distribution feeders, that are not captured by the Cambium data.

More detail about the methodology employed for the analysis is provided in the NREL Data Catalog.

4.0 Results

In addition to the summary results provided in this section and in the appendicies, detailed results for the contiguous United States can be downloaded from the NREL Data Catalog.[15] Results include annual load patterns, charts and tables of results for each individual measure studied, organized by state.

4.1 Lighting Measures

The lighting efficiency measures modeled use occupancy controls and improvements in daylighting controls in perimeter zones. Demand flexibility measures reduce lighting during peak hours while maintaining occupant comfort and safety.[16]

[14] The utility tariff codes representing the utility rate structure that was applied to all the bill savings calculations are available in the NREL Data Portal. These codes can be used to look up the rate structure in the Utility Rate Database.

[15] The complete set of results organized by state is available for download at: https://data.nrel.gov/submissions/205.

[16] Although many large office buildings across the United States have already switched to LEDs, this transition is ongoing. Most of this transition (both in the model and in the real world) represents transitioning from compact and standard fluorescent lighting to LEDs. For instance, in 2018, the U.S. Energy Information Administration (EIA) estimated that LEDs were used in 44% of commercial buildings compared to 68% for standard fluorescent and 19% for compact fluorescent. The EIA estimates that by 2050 LEDs will provide up to 95% of commercial lighting needs (EIA 2021). Although the savings are not as high as with incandescent bulbs, significant savings can still be realized by transitioning from fluorescent lamps to LEDs.

4.1.1 Lighting Measure Impact on Load

Lighting measures result in limited load reductions during most of the year but with large reductions in select hours. The efficiency and demand flexibility measures reduce load in a single office building by up to 80 MWh per year in regions with the greatest load reduction potential. Regions with the highest potential to reduce lighting load, include Texas, Kansas, Arkansas, Mississippi, and Louisiana. This is because the lighting building loads in these states overlapped with the timing of measure implementation.[17] States with the lowest annual load reduction potential (~23 MWh) are in the northeast (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont). Individual state load reductions are listed in the Appendix in Table 6.

The results of this analysis likely *underestimate* the potential for lighting efficiency and well-timed demand response to reduce lighting load during peak pricing hours. This is because the lighting component load profiles used in the modeling assume that lighting load in large offices drastically decreases after normal working hours (6 p.m.), and, as a result, there is limited load reduction potential from implementing the lighting measures; however, informal observations of lighting in large office buildings indicate that lighting load can remain near the daytime level later in the evening. The second phase of this research, currently underway, aims to improve measure deployment to better represent real-world conditions.

4.1.2 Lighting Measure Impact on Electricity Bill Savings

The southern and midwestern states are found to have the greatest potential for bill savings from lighting efficiency and demand flexibility, with annual bill savings in the range of $7,000–8,000 for a single 500,000-ft^2 large office building.[18] Causation is difficult to determine—these higher savings could be caused by higher than average retail tariff rates, higher than average load reductions, or better than average alignment between load reduction and higher-priced tariff periods. While it is relatively straightforward to determine if an office building faces higher than average rates or sees higher than average load changes, the interaction between these variables at an hourly level is difficult to isolate in average annual savings.

These savings represent reductions in bills solely by changing load patterns patterns (both in terms of reductions and load shifting), and they *do not* reflect any compensation for participation in a customer-facing utility program (such as a demand response program) or aggregation into an independent system operator market (such as part of a virtual power plant).

Analyzing all rate structures and locations modeled reveals a wide range of bill savings. A building owner might realize $5,000 or $13,000 in savings from implementing the same measures, depending on the assigned rate structure. This highlights the influence of rate structure and the need for building energy managers to investigate different rate options for their building(s). In some cases, switching to a different rate in conjunction with installing measures can yield additional savings. The energy manager could investigate utility rates that result in the lowest annual utility bill, which may not be the one that results in the largest savings from any single efficiency measure.

[17] Recall that measures were implmemented to reduce regional system peak loads.

Figure 1 shows the range of savings across all relevant rate structures analyzed. The map shows the bill savings by state, whereas the table details the top 10 states. Appendix C.2 provides the same results for all 48 states in the contiguous United States.

4.1.3 Lighting Measure Impact on CO_2 Emissions Reductions

The greatest potential for reducing CO_2 emissions from lighting efficiency and demand response is found in the north-central regions, in the Midwest, in West Virginia, and in Mississippi.

The ability of a measure to reduce CO_2 emissions depends on several factors: (1) the magnitude of the load reductions associated with the measure, (2) the carbon intensity of the generating sources on the margin, and (3) the coincidence between the load reductions and the marginal CO_2 emissions rates. Determining which of these factors was most prominent in the results is difficult and was not the focus of this analysis, and all factors contributed in each case to some degree. Several points regarding these factors include:

- There is limited ability to reduce lighting levels below those modeled for the energy-efficiency measure while maintaining occupant comfort, limiting the load reductions associated with the demand response measure. Most of the annual load reduction is obtained from the energy-efficiency measure.[19]
- States that have high emitting sources *on the margin* during the hours that measures reduced building load have a larger potential for energy-efficiency and demand response measures to reduce CO_2 emissions.
- States with high potential for CO_2 emissions reductions do not necessarily have the highest overall annual emissions from the power sector. States with low annual CO_2 emissions from the power sector do not necessarily have low potential for emissions reductions. This is because the potential for emissions reductions is dependent on the coincidence between the high emissions periods and the timing of the load reductions from measures.
- Marginal emissions rates can vary considerably across the year depending on grid conditions. The results provided here might not represent the maximum potential for CO_2 emissions reduction potential, since measure-induced load reductions were not intentionally aligned with marginal emissions rates.

In summary, to effectively capture the CO_2 savings potential, industry and state coordination will be needed to forecast which fuel sources are on the margin and then to create incentives for end users to reduce load during expected high CO_2 emissions hours.

4.1.4 Lighting Measure Impact on Bulk Power Costs

States in the south and northeast are found to have the greatest potential to reduce bulk power costs through lighting efficiency and demand flexibility, with savings in the top 10 states between $2,890–3,240 from a single 500,000-ft^2 large office building. Energy efficiency is responsible for most bulk

[19] This is revealed by comparing the CO_2 emissions reductions from the combined measures against individual lighting energy-efficiency and demand response measures across the country (see Data Catalog and Appendix). The median emissions reduction from the combined measures is 20,900 kg; the median emissions reduction from the energy-efficiency measure is 19,700 kg; and the median emissions reduction from the demand response measure is 2,200 kg.

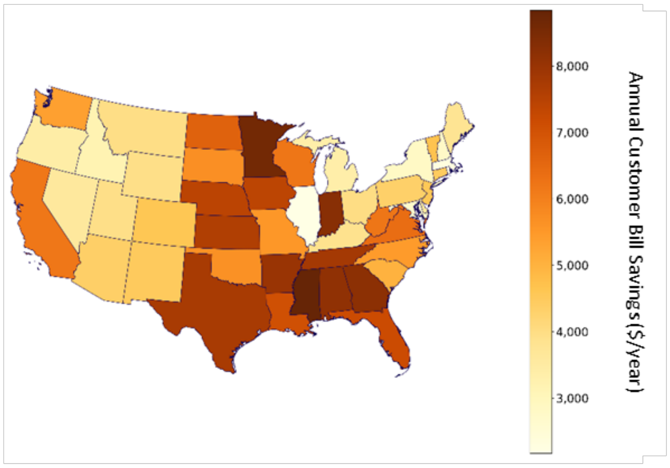
power cost savings across the United States.[20] The Pennsylvania case study (Section 4.3.2) elucidates how the savings are realized.

Note the difference in operational savings among states in the Western Interconnection, the Eastern Interconnection, and the Electric Reliability Council of Texas (Figure 1). The regional variation is largely a result of higher bulk power costs in the Eastern Interconnection. Lighting measures also have a greater load-reducing effect in the southeastern states, possibly because high-efficiency lighting has a secondary effect of reducing summer cooling load (see Appendix A).

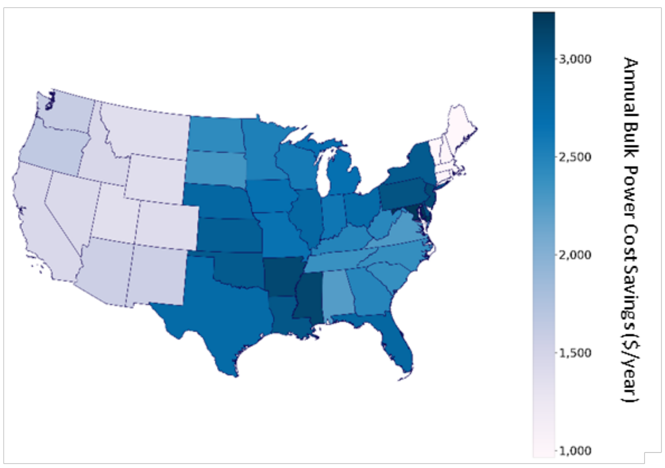
The exception to the regional split is in New England, which has notably lower operational cost savings than the rest of the Eastern Interconnection. This is a result of lower marginal bulk power costs in New England compared with the rest of the Eastern Interconnection.

[20] The savings from the individual measures do not sum to the savings associated from the combined energy-efficiency and demand response measures. This is due to the interplay of efficiency and demand response measures. For more information on this interplay, see Langevin et al. (2021).

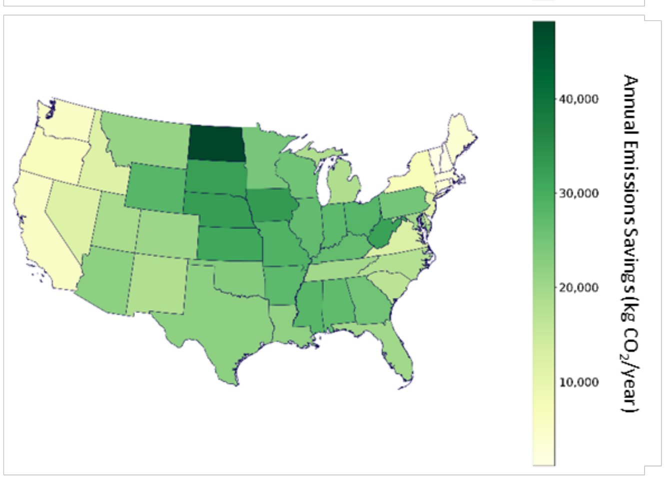
Lighting and Demand Flexibility
Potential in Single Large Office Building, by State



State	Annual Customer Bill Savings ($/year)
Mississippi	$8,840
Minnesota	$8,620
Indiana	$8,290
Georgia	$8,200
Alabama	$8,150
Arkansas	$7,990
Tennessee	$7,810
Texas	$7,760
Kansas	$7,630
Nebraska	$7,450



State	Annual Bulk Power Cost Savings ($/year)
Maryland	$ 3,240
Mississippi	$ 3,120
Arkansas	$ 3,100
New Jersey	$ 3,080
Delaware	$ 3,040
Pennsylvania	$ 3,000
Louisiana	$ 2,980
Oklahoma	$ 2,940
New York	$ 2,930
Kansas	$ 2,890



State	Annual Emissions Savings (kg CO_2/year)
North Dakota	48,200
Iowa	33,100
Nebraska	32,700
South Dakota	32,400
West Virginia	31,900
Kansas	30,900
Missouri	28,900
Ohio	28,200
Wyoming	28,100
Mississippi	28,100

Note: Color scales differ for each metric in order to show regional differences. CO_2 emission calculations are based on levelized marginal emissions data from NREL's Cambium dataset.

Figure 1. Impact of implementing lighting efficiency and demand flexibility measures in a single large office building by state

4.2 Cooling Measures

The cooling efficiency measure upgrades an existing water-cooled centrifugal chiller to a chiller with 7.0 coefficient of performance (COP). We combine the efficiency measure with two different cooling demand response measures. The first sheds cooling load by making GTAs (relaxing the thermostat set point during peak hours). The second is a precooling measure that shifts load by adjusting the zone cooling temperatures downward for the 4 hours preceding the peak period without making any changes to the set point during the peak period.[21] Precooling relies on the thermal mass of the building to reduce load during the peak while maintaining occupant comfort, making buildings with large thermal mass best suited for this type of demand response measure. Cooling demand response is relatively easy to implement because there is little to no capital cost, assuming that the building is fitted with a building energy management system.

4.2.1 Cooling Measure Impact on Load

The load-shedding cooling measure provides limited load reductions during most of the year combined with large reductions in select hours. The precooling measure provides moderate total load reductions throughout the year and significant load increases in specific precooling periods. States with the highest potential to reduce annual cooling load include Texas, Arkansas, Louisiana, and Mississippi; Texas shows a 28.5-MWh reduction in a single large office building when implementing the efficiency and load-shedding measures. Implementing the same measures in cooler climate states such as Wisconsin and in the northeast yielded only 3.2 MWh of reduction. Individual state load reductions are listed in Appendix A.

4.2.2 Cooling Measure Impact on Electricity Bill Savings

Modeled results indicate strong differences in the distribution of states' potential for annual bill savings between the two types of cooling measures.

The measure that combines efficiency with load shedding provides the greatest savings in the southeastern states (where summer cooling load is high) and, notably, in West Virginia and Maine. In the top 10 states (Figure 2), median annual bill savings range from nearly $4,000 (Maine) to approximately $2,000 (Ohio), with possible savings of more than $5,000 for some rate structures. Tariff structures likely drive the bill savings in both Maine and Ohio because the load reduction resulting from the cooling measure is small relative to the load reduction in the southeast (see Appendix A).

The cooling efficiency and precooling combination results in less savings overall and a much less pronounced regional pattern in potential savings, due to differences in rate structures across regions. Select southeastern, Mid-Atlantic, and northeastern states have higher savings potential. In the top 10 states, median annual bill savings range from >$3,000 (Maine) to $560 (Connecticut), and potential bill *increases* of more than $2,000 are shown under some rate structures.

Bill increases are likely due to (1) significant load increases in specific precooling periods under the precooling measure and (2) moderate total load reductions throughout the year. Precooling increases

[21] Peak hours as defined in the modeling are provided in Table 2. The model does not consider peak grid operating costs or CO_2 emissions when deploying the demand response measures. Demonstration projects have confirmed that precooling can be achieved without sacrificing occupant comfort. For example, a case study of the John F. Shea Federal Building reported shifting 80%–100% of chiller power from on-peak to off-peak periods on days when outside temperatures exceeded 90°F, with no complaints from building users (GSA 2021).

building load beyond the baseline for 4 hours of the day without changing the thermostat set point during the peak period. Increased load during the precooling hours can trigger higher energy rates (for rate structures with tiered pricing) as well as higher demand charges (for rate structures that include demand charges). The wide variation in potential bill impacts points to the importance of identifying how the implementation of an energy measure in a specific building will change the load pattern and how this interacts with the specific rate tariff to which the building is subject. It should be noted again that the pre-cooling strategy was not calibrated to respond to specific retail tariffs, and these results point to the need for additional study on targeted strategies to benefit both the customer and the power system.

4.2.3 Cooling Measure Impact on CO_2 Emissions Reductions

The southern states of Arkansas, Florida, Mississippi, and Louisiana top the list for potential savings from both the load-shedding and precooling measure combinations. These states (along with others in the southeast) tend to have larger load reductions associated with the cooling measures than the rest of the country (see Appendix A), which is likely due to larger cooling baseline loads. States in the southeast also have higher CO_2 emissions rates relative to much of the rest of the country, which contributes to the potential for CO_2 savings.[22]

Some exceptions to the trend include North Dakota and Arizona, which also show good potential for savings from the load-shedding measure. North Dakota has the highest long-run marginal emissions rate in the country (with a median value of approximately 600 kg CO_2/MWh). In Arizona, the high potential for savings might be due to a combination of a relatively high long-run marginal emissions rate (approximately 370 kg CO_2 kg/MWh) and higher cooling load reductions. Recall that a measure's ability to reduce emissions depends on (1) the magnitude of the load reductions from the measures, (2) the carbon intensity of the generating sources, and (3) the coincidence between the timing of the load reductions and the hourly marginal emissions rates.

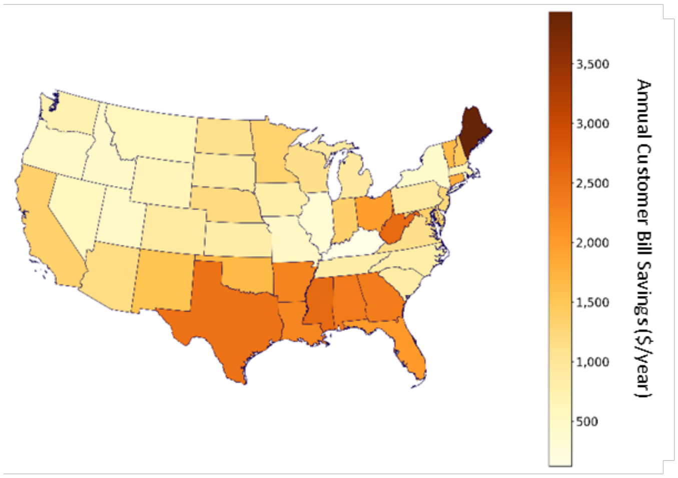
4.2.4 Cooling Measure Impact on Bulk Power Costs

There are clear regional patterns in the grid impacts of the cooling efficiency and load-shedding measures, with the largest potential for savings in southern states (Florida, Mississippi, and Louisiana top the list). Savings are likely driven by the cooling load reductions in the warm climates of these states. Note that this contrasts with the lighting measure results, which seem to be driven more by wholesale energy prices than load reductions.

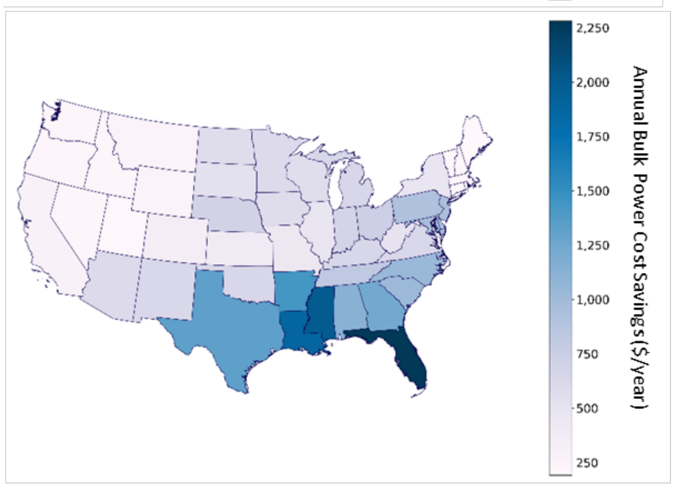
For the cooling efficiency and precooling measure combination, bulk power cost savings potential is lower and less geographically aligned. Some states see bulk power cost *increases* under the cooling efficiency and precooling measure, which is likely due to some load being shifted to more expensive hours for the grid. These trends are similar to the bill savings results.

[22] For instance, for the entire year across the southeastern states (subjectively chosen by the authors to include Alabama, Arkansas, Florida, Georgia, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and Texas), the median long-run marginal emissions rate is 325 kg CO_2/MWh compared to 265 kg CO_2/MWh for the rest of the country.

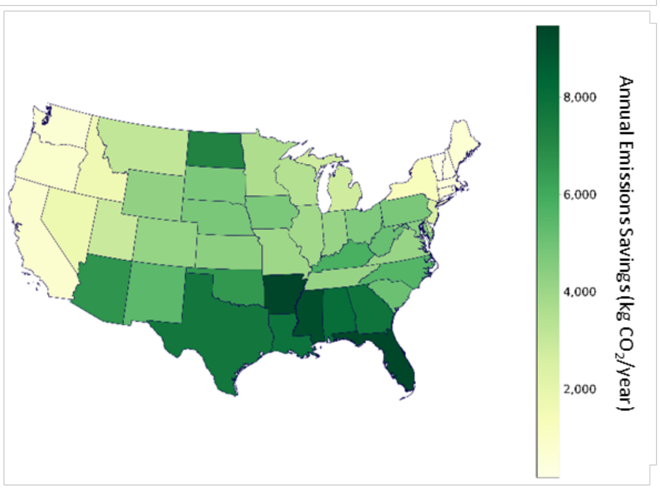
Cooling Efficiency and Load Shedding Potential in Single Large Office Building, by State



State	Annual Customer Bill Savings ($/year)
Maine	$3,940
Mississippi	$2,580
West Virginia	$2,580
Texas	$2,460
Alabama	$2,380
Georgia	$2,360
Arkansas	$2,280
Louisiana	$2,250
Florida	$2,020
Ohio	$1,980



State	Annual Bulk Power Cost Savings ($/year/building)
Florida	$ 2,280
Mississippi	$ 2,000
Louisiana	$ 1,880
Arkansas	$ 1,440
Texas	$ 1,330
Georgia	$ 1,240
Alabama	$ 1,130
North Carolina	$ 1,030
South Carolina	$ 1,030
Maryland	$ 970

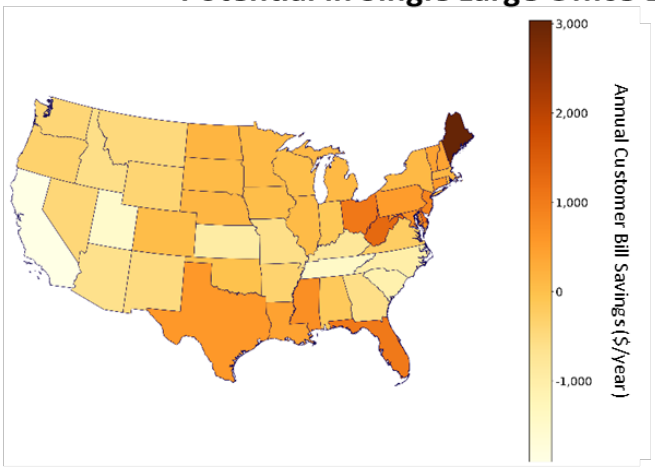


State	Annual Emissions Savings (kg CO_2/year/building)
Arkansas	9,500
Florida	9,400
Mississippi	9,200
Alabama	8,100
Louisiana	7,900
Georgia	7,800
Texas	7,700
North Dakota	7,200
Arizona	6,700

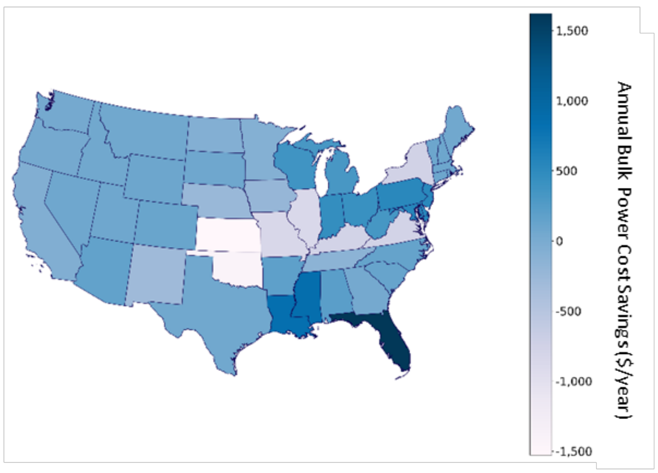
Note: Color scales differ for each metric in order to show regional differences. CO_2 emission calculations are based on levelized marginal emissions data from [NREL's Cambium dataset](#).

Figure 2: Impact of implementing cooling efficiency and load-shedding measures in a single large office building by state

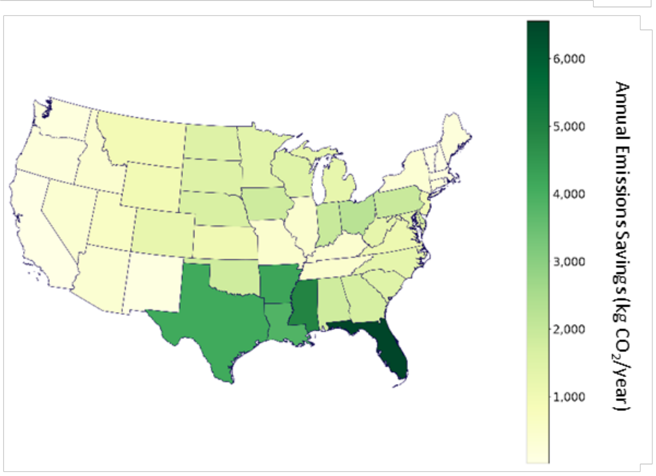
Cooling Efficiency and Load Shifting Potential in Single Large Office Building, by State



State	Annual Customer Bill Savings ($/year)
Maine	$3,040
West Virginia	$1,320
Delaware	$1,200
Ohio	$1,060
Florida	$1,040
New Jersey	$890
Maryland	$730
Mississippi	$710
Texas	$580
Connecticut	$560



State	Annual Bulk Power Cost Savings ($/year/building)
Florida	$ 1,620
Mississippi	$ 870
Louisiana	$ 840
Maryland	$ 560
Delaware	$ 540
New Jersey	$ 540
Pennsylvania	$ 540
Indiana	$ 450
Ohio	$ 420
Wisconsin	$ 370



State	Annual Emissions Savings (kg CO_2/year/building)
Florida	6,600
Mississippi	4,900
Arkansas	4,200
Texas	3,900
Louisiana	2,300
Ohio	2,000
Indiana	2,000
Pennsylvania	1,900
Iowa	1,900

Notes: Negative values indicate that the increased costs to the power system due to precooling the building exceed any savings to the power system associated with reduced consumption after the precooling period. Negative values indicate that the increased costs to the power system due to precooling the building exceed any savings to the power system associated with reduced consumption after the precooling period.

Figure 3: Impact of implementing cooling efficiency and load-shifting measures in a single large office building by state

4.3 Understanding Impacts at a State Level

4.3.1 Scaling Building-Level Impacts to the State Level

The potential savings estimates reported in this analysis are for *individual* large office buildings. We do not make assumptions about the level of adoption of the measures (that is, how many buildings would adopt the measures); however, regulators and state policymakers are more likely be interested in the potential at a state level. A simplistic method to scale the building-level results to the state level is to multiply the potential reported here by the number of large office buildings in a state.

ComStock provides information regarding building square footage at a county level. The total square footage of large office space by state was divided by 498,588 ft^2 to estimate the number of buildings that match the specifications of the single large office building we modeled (Table 3). According to the data set, New York, California, and Texas have the largest number of large office buildings, whereas North Dakota, South Dakota, Wyoming, and Montana have the fewest. These numbers should be taken only as rough estimates, since they are based on total square footage by state and not actual building counts.

Table 3: Number of Large Office Buildings (>500,000 ft^2) According to ComStock

State	Number of Large Office Buildings	State	Number of Large Office Buildings
Alabama	80	Nebraska	40
Arizona	90	Nevada	20
Arkansas	45	New Hampshire	10
California	835	New Jersey	275
Colorado	120	New Mexico	10
Connecticut	115	New York	1,515
Delaware	20	North Carolina	220
Florida	415	North Dakota	5
Georgia	265	Ohio	305
Idaho	35	Oklahoma	60
Illinois	645	Oregon	70
Indiana	135	Pennsylvania	375
Iowa	70	Rhode Island	25
Kansas	45	South Carolina	65
Kentucky	65	South Dakota	5
Louisiana	65	Tennessee	205
Maine	25	Texas	965
Maryland	225	Utah	65
Massachusetts	445	Vermont	10
Michigan	210	Virginia	315
Minnesota	240	Washington	185
Mississippi	25	West Virginia	15
Missouri	200	Wisconsin	85
Montana	5	Wyoming	5

4.3.2 Case Study: Lighting in Pennsylvania

This section explores the impact of implementing lighting efficiency and demand response in Pennsylvania to show how the results can be used at the state level. Our building stock data in Table 3 indicates there are 375 large office buildings in Pennsylvania that meet the specifications of the prototype building we modeled. Table 4 summarizes the annual bill savings, bulk power cost savings, and CO_2 emissions reductions for a single building in the state and across all buildings in the state.

The NREL Data Catalog has detailed results on load reduction and charts that overlaps the load reduction, marginal operating costs, and grid emissions.

Table 4: Impact of Implementing Lighting Efficiency and Demand Response in Pennsylvania

	Single Building	All Large Office Buildings in State (Assuming n = 375)	U.S. Ranking Individual Building/ Statewide (Of 48 States)
Load reduction (kWh/yr)	68,200 kWh	25,600 MWh	12th/5th
Bill savings ($/yr) median (range)	$4,340 ($1,410–$14,680)	$1,628,000	31st/8th
Annual bulk power cost reductions ($/yr)	$3,000	$1,124,400	6th/6th
CO_2 emissions reductions (kg/yr)	24,900 kg	9,352,100 kg	18th/4th

As shown in the U.S. ranking column in Table 4, at the individual building level, Pennsylvania has relatively low bill savings and CO_2 emissions reductions opportunities, modest load reduction opportunities, and good bulk power cost reduction opportunities compared to other states; however, the large number of large office buildings in Pennsylvania (375) gives the state a high ranking across all metrics compared to other states. Pennsylvania ranks fifth for potential load reductions, eighth for bill savings, sixth for bulk power cost reductions, and fourth for CO_2 emissions reductions at a state level.

This highlights the potential impact of implementing measures across many buildings and points to the role that state-level policymakers can play in increasing the impact of efficiency and demand response measures in their states through programs and policies that incentivize deployment.

4.3.3 Case Study: Cooling in Texas

This section details the results of implementing cooling measures across Texas. Building stock data in Table 5 indicate that there are approximately 965 large office buildings in Texas that meet the specifications of the prototype building we modeled. Table 5 and Table 6 summarize the annual bill savings, bulk power cost savings, and CO_2 emissions reductions for a single building in the state and across all buildings in the state for both cooling measures.

The NREL Data Portal has detailed data on the building load in a large office building in Texas before and after the cooling measures are applied on a typical summer weekday and a graph overlapping the load reductions and the marginal load conditions for operating costs and grid emissions.

Table 5: Impact of Implementing Efficiency and Load Shedding in Texas

	Single Building	All Large Office Buildings in State (Assuming n = 965)	U.S. Ranking Individual Building/ Statewide (Of 48 States)
Load reduction (kWh/yr)	28,500 kWh	27,500 MWh	1st/1st
Bill savings ($/yr) median (range)	$2,460 ($1,050–$5,390)	$2,376,600	4th/1st
Annual bulk power cost reductions ($/yr)	$1,330	$1,285,000	5th/1st
CO_2 emissions reductions (kg/yr)	7,650 kg	7,386,700 kg	7th/1st

Table 6: Impact of Implementing Efficiency and Precooling in Texas

	Single Building	All Large Office Buildings in State (Assuming n = 965)	U.S. Ranking Individual Building/ Statewide (Of 48 states)
Load reduction (kWh/yr)	11,770 kWh	11,360 MWh	2nd/1st
Bill savings ($/yr) median (range)	$580 (-$2,230–$1,430)	$561,160	9th/1st
Annual bulk power cost reductions ($/yr)	$70	$63,980	29th/7th
CO_2 emissions reductions (kg/yr)	4,100 kg	3,961,100 kg	4th/1st

Texas ranks high in potential impact across bill savings, bulk power cost reductions, and emissions reductions, especially for the cooling efficiency and load-shedding measure combination. The large number of qualifying buildings in Texas (965) means that the state ranks very high in terms of potential for impact across both measures. (Texas ranks first in the country for all metrics except bulk power cost reductions for precooling.)

Comparing the total potential for savings across the load-shedding and precooling measures, the load-shedding measure has more potential for impact. This is a result of increased cooling load during the precooling period, which increases emissions and bulk power costs. It is possible that better timing of the precooling period could increase the potential for impact, but shifting the load to alternate times of day was beyond the scope of this study and is a topic for future analysis.

4.4 Understanding the Drivers of Measure Impacts

When interpreting these results, it is interesting to consider the underlying factors that might be driving the impacts at the state level. Some factors are listed here; however, this report does not attempt to confirm the extent to which each factor is responsible for the estimated cost and emissions savings—i.e., we did not attempt to verify causation.

1. **Magnitude of component building load prior to measure implementation**: The extent to which a given measure can reduce building load strongly depends on the magnitude of the building load component that is affected by the measure. For instance, measures that reduce cooling demand will have greater opportunity to impact customer bills and grid conditions in regions where cooling demands are high (e.g., the southeast). Thus, some measure impacts may exhibit strong geographic patterns.

2. **Local tariff structures, billing practices, and coincidence of measure**: The ability of a measure to impact customer bills is fundamentally linked to the magnitude and structure of the retail tariff rates. The average cost of electricity and the presence of various tariff elements—such as minimum bills, fixed costs, demand charges, and time-of-use rates—impact the potential bill savings from measures. Generally, in locations with higher local electricity rates, measures offer more cost savings on customer bills in absolute terms. Measures do not impact some tariff elements, such as fixed costs and minimum bills. The time-of-use and demand charge elements can be significantly impacted by the load changes induced by measures. For instance, if precooling in a building results in increased demand during a lower-priced period and decreased demand during a higher-priced period, then the measure will likely induce larger customer bill savings.

3. **Local grid conditions and coincidence of measure**: The ability of measures to reduce bulk power costs and emissions is strongly impacted by the marginal grid conditions. Locations with consistently more expensive marginal conditions or higher marginal emissions rates, caused by local transmission constraints or the generation mix, will offer more opportunities (in absolute terms) to reduce bulk power costs and emissions. For instance, measures might have greater impacts on emissions in states where coal and natural gas are frequently on the margin compared to locations with more solar photovoltaics, hydropower, and wind generation. The coincidence between local grid conditions and measure-induced load reductions will also influence the overall impact. For instance, if large load reductions are enabled in the late afternoon by cooling load shedding, and if that coincides with higher demand, more expensive marginal generation, and more polluting marginal generation in the state, then the measure will likely have a larger impact on bulk power costs and emissions.

5.0 Conclusions and Next Steps

The buildings sector represents a significant opportunity to simultaneously pursue decarbonization goals while providing cost savings to energy end users and the power system. Given the right combination of technology and price signals, building occupants can modify their load patterns to take advantage of lower-priced and lower-emissions times of day without sacrificing occupant comfort or power system reliability.

This analysis represents a first approximation of the magnitude of the benefits of modifying lighting and cooling loads in representative large office buildings in 48 U.S. states. We estimate benefits accruing to both building owners and the power system through bill savings, bulk power costs, and grid emissions. In addition to the estimated savings potential results presented here, overarching conclusions include:

- To effectively capture the CO_2 savings potential, industry and state coordination is needed to verify which fuel source is on the margin and then to create incentives for end users to reduce load during expected high CO_2 emissions hours.

- It is important to identify how implementing an energy measure in a specific building will change the building load pattern and the interaction of this load change with the specific rate tariff to which the building is subject. This is demonstrated by the wide variation in bill impacts of implementing the precooling measure.

- The estimated potential for savings should be compared to the difficulty or cost of implementing a particular measure. Measures that are more difficult to implement entail deep building retrofits or modifying building occupant behavior. For instance, swapping out incandescent bulbs for LEDs is straightforward, whereas modifying a building envelope or installing a higher-efficiency cooling system is more labor intensive and costly. Decision makers might choose to incentivize lower-effort initiatives first, or they might choose to offer additional incentives for measures that are more difficult to implement.

    - Lighting and cooling demand response measures studied here are relatively easy to capture because they have little or no capital cost to implement, assuming that the building already has a building energy management system.

- Regular updates to data sets and analyses of the potential for implementing efficiency and demand response measures are critical. Grid conditions depend on a variety of factors, such as system-wide load, the availability of variable renewable energy, the generating capacity mix, transmission capacity levels, and many more. As the power system evolves, marginal grid conditions will also change, which could increase or decrease the potential for a particular measure to influence bulk power costs or emissions.

- Regulators and policymakers are well positioned to facilitate and coordinate the necessary actions between the electric power industry and building energy managers to develop appropriate price signals to consumers, which would make realizing the potential savings reported here more feasible.

This analysis does not actively align the load reductions achieved through demand flexibility with existing grid conditions in specific locations. Intentional alignment of power system conditions and customer price signals is necessary to maximize both operational cost and emissions savings. This would require either the adjustment of retail tariff designs to correspond with grid conditions or coordinated data sharing and real-time communications. Such coordination may be facilitated in the future by energy aggregators that provide a link between individual buildings and the wholesale energy market. The Federal Energy Regulatory Commission’s Order 2222 facilitates the development of market structures to capture the value of distributed resources such as distributed generation, energy storage and controllable flexible loads, however the role and value of demand flexibility in these future markets remains unclear.

In Phase 2 of this analysis, we aim to refine the potential savings reported here by more actively aligning measure deployment with the metrics of interest (costs and emissions). We also plan to explore additional measures and building types. In future endeavors, the estimates of potential savings could be refined by (1) emulating how energy end users would respond to various types of price signals, (2) exploring a wider variety of marginal grid conditions by comparing across additional future grid scenarios, and (3) exploring the value of switching fuels in buildings (e.g., switching from natural gas to electric heating).

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Appendix A. Detailed Results of State Potential for Load Reduction and Savings from Lighting and Cooling Efficiency and Demand Flexibility Measures

A.1 Lighting Energy Efficiency and Demand Response

Table 7: Building Load Reduction by Region and State From Lighting Efficiency and Demand Flexibility Measure

EIA EMM Region	States Included	Total Annual Load Reduction per Building (kWh)	Peak Load Reduction (kW)	Peak Timing
ERCT	TX	80,605	22.88	August 03, 3:00 PM
SPNO	KS	77,226	20.28	July 20, 3:00 PM
SRDA	AR, MS, LA	76,990	23.23	July 07, 3:00 PM
SPSO	OK	72,876	52.29	August 02, 3:00 PM
MROW	IA, MN, NE, ND, SD	71,216	17.89	June 30, 2:00 PM
RFCE	DE, MD, NJ, PA	68,184	21.67	July 20, 3:00 PM
SRGW	IL, MO	68,034	18.27	July 20, 3:00 PM
NYUP	NY	65,392	21.19	July 20, 3:00 PM
RFCW	IN, OH, WV	61,913	24.06	July 20, 3:00 PM
MROE	WI	61,506	24.17	June 30, 2:00 PM
FRCC	FL	60,997	17.78	July 21, 3:00 PM
RFCM	MI	60,675	25.37	July 20, 3:00 PM
SRSE	AL, GA	53,885	15.45	July 07, 3:00 PM
SRCE	KY, TN	53,573	22.72	August 02, 3:00 PM
SRVC	NC, SC, VA	51,515	28.01	August 02, 3:00 PM
AZNM	AZ, NM	49,550	36.06	August 16, 3:00 PM
RMPA	CO	45,788	12.77	June 26, 3:00 PM
NWPP	ID, MT, NV, OR, UT, WA, WY	45,638	13.45	August 10, 3:00 PM
CAMX	CA	44,536	11.74	August 17, 2:00 PM
NEWE	CT, ME, MA, NH, RI, VT	23,187	9.94	July 20, 3:00 PM

Table 8: Building Potential for Bill Savings by State From Lighting Efficiency and Demand Flexibility Measure

State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)	State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)
Alabama	$8,150	$8,150	**Nebraska**	$7,450	$12,110
		$8,010			$4,360
Arizona	$4,380	$7,000	**Nevada**	$3,620	$4,650
		$960			$ -
Arkansas	$7,990	$8,560	**New Hampshire**	$2,780	$5,460
		$4,500			$2,780
California	$6,200	$13,210	**New Jersey**	$4,580	$8,170
		$3,760			$2,460
Colorado	$4,610	$11,550	**New Mexico**	$4,520	$9,860
		$2,830			$3,520
Connecticut	$4,480	$14,130	**New York**	$2,830	$12,190
		$1,850			$(960)
Delaware	$3,560	$3,560	**North Carolina**	$5,480	$7,470
		$3,560			$4,180
District of Columbia	$1,990	$2,350	**North Dakota**	$6,660	$6,740
		$1,630			$5,410
Florida	$7,180	$9,700	**Ohio**	$4,010	$8,450
		$3,060			$1,900
Georgia	$8,200	$9,420	**Oklahoma**	$5,680	$9,490
		$3,520			$3,520
Idaho	$3,190	$4,370	**Oregon**	$3,440	$5,300
		$2,490			$ -
Illinois	$2,170	$5,220	**Pennsylvania**	$4,340	$14,680
		$1,980			$1,410
Indiana	$8,290	$9,820	**Rhode Island**	$2,270	$2,270
		$5,940			$2,270
Iowa	$7,410	$8,380	**South Carolina**	$5,010	$5,680
		$5,220			$4,740

State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)	State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)
Kansas	$7,630	$9,130	**South Dakota**	$5,690	$10,530
		$2,200			$3,280
Kentucky	$3,880	$11,410	**Tennessee**	$7,810	$12,210
		$770			$2,140
Louisiana	$7,090	$9,790	**Texas**	$7,760	$10,640
		$3,350			$3,790
Maine	$3,800	$3,800	**Utah**	$3,950	$4,040
		$2,040			$2,830
Maryland	$2,700	$6,130	**Vermont**	$4,690	$12,940
		$1,630			$4,690
Massachusetts	$2,330	$9,970	**Virginia**	$6,420	$10,340
		$2,010			$4,860
Michigan	$3,390	$9,220	**Washington**	$5,370	$6,360
		$1,390			$2,950
Minnesota	$8,620	$9,300	**West Virginia**	$6,220	$7,010
		$3,140			$4,320
Mississippi	$8,840	$13,470	**Wisconsin**	$6,210	$10,930
		$5,310			$3,850
Missouri	$5,540	$8,590	**Wyoming**	$3,950	$5,780
		$2,310			$1,900
Montana	$3,970	$7,830			
		$1,900			

Note that the retail tariffs associated with the “baseline” and “efficient” scenarios used to calculate the median bill savings shown here can be found in the NREL Data Portal. The tariffs are referred to by their unique tariff codes, which can be used to locate a description of the tariff in the Utility Rate Database.

Table 9: Building Potential for Bulk Power Cost Savings by State From Lighting Efficiency and Demand Flexibility Measure

State	Annual Reduction in Bulk Power Costs (Single Building) ($/yr)	State	Annual Reduction in Bulk Power Costs (Single Building) ($/yr)
Alabama	2,250	**Nebraska**	2,780
Arizona	1,570	**Nevada**	1,430
Arkansas	3,100	**New Hampshire**	1,000
California	1,450	**New Jersey**	3,080
Colorado	1,390	**New Mexico**	1,560
Connecticut	1,000	**New York**	2,930
Delaware	3,040	**North Carolina**	2,400
Florida	2,790	**North Dakota**	2,430
Georgia	2,480	**Ohio**	2,740
Idaho	1,460	**Oklahoma**	2,940
Illinois	2,780	**Oregon**	1,640
Indiana	2,610	**Pennsylvania**	3,000
Iowa	2,660	**Rhode Island**	1,010
Kansas	2,890	**South Carolina**	2,390
Kentucky	2,490	**South Dakota**	2,330
Louisiana	2,980	**Tennessee**	2,370
Maine	970	**Texas**	2,730
Maryland	3,240	**Utah**	1,360
Massachusetts	990	**Vermont**	970
Michigan	2,660	**Virginia**	2,270
Minnesota	2,520	**Washington**	1,600
Mississippi	3,120	**West Virginia**	2,460
Missouri	2,650	**Wisconsin**	2,580
Montana	1,370	**Wyoming**	1,370
Note that although bill savings has a value for the District of Columbia, Cambium does not aggregate results for that region; therefore, it is excluded from estimates for grid impacts.			

Table 10: Building Potential for Grid Emissions Savings by State From Lighting Efficiency and Demand Flexibility Measure

State	Annual Grid CO_2 Emissions Reduction (Single Building) (kg CO_2 per Building/yr)	State	Annual Grid CO_2 Emissions Reduction (Single Building) (kg CO_2 per Building/yr)
Alabama	27,180	**Nebraska**	32,720
Arizona	22,260	**Nevada**	12,040
Arkansas	27,520	**New Hampshire**	1,150
California	5,340	**New Jersey**	11,050
Colorado	20,590	**New Mexico**	18,360
Connecticut	3,470	**New York**	7,110
Delaware	15,380	**North Carolina**	17,900
Florida	20,020	**North Dakota**	48,210
Georgia	25,310	**Ohio**	28,220
Idaho	11,790	**Oklahoma**	23,540
Illinois	26,870	**Oregon**	6,460
Indiana	27,540	**Pennsylvania**	24,940
Iowa	33,100	**Rhode Island**	2,040
Kansas	30,920	**South Carolina**	16,880
Kentucky	26,810	**South Dakota**	32,360
Louisiana	21,990	**Tennessee**	19,960
Maine	3,880	**Texas**	22,160
Maryland	19,980	**Utah**	19,140
Massachusetts	2,660	**Vermont**	1,100
Michigan	18,510	**Virginia**	12,730
Minnesota	24,840	**Washington**	5,370
Mississippi	28,140	**West Virginia**	31,930
Missouri	28,930	**Wisconsin**	25,430
Montana	21,280	**Wyoming**	28,140
Although bill savings has a value for the District of Columbia, Cambium does not aggregate results for that region; therefore, it is excluded from estimates for grid impacts.			

A.2 Cooling Energy Efficiency and Load Shedding

Table 11: Load Impact From Cooling Energy Efficiency and Load Shedding

EIA EMM Region	States Included	Total Annual Load Reduction per Building (kWh)	Peak Load Reduction (kW)	Peak Timing
ERCT	TX	28,530	8.67	August 03, 3:00 PM
SRDA	AR, LA, MS	26,044	7.96	July 07, 3:00 PM
FRCC	FL	24,814	5.77	July 21, 3:00 PM
SPSO	OK	21,296	9.02	August 02, 3:00 PM
SRSE	AL, GA	15,944	6.49	July 07, 3:00 PM
AZNM	AZ, NM	15,882	4.31	August 16, 3:00 PM
SRVC	NC, SC, VA	14,045	7.6	August 02, 3:00 PM
RFCE	DE, MD, NJ, PA	13,082	40.44	July 20, 3:00 PM
SPNO	KSZ	11,707	4.95	July 20, 3:00 PM
SRCE	KY, TN	11,068	5.28	August 02, 3:00 PM
MROW	IA, MN, NE, ND, SD	10,500	2.97	June 30, 2:00 PM
RMPA	CO	10,184	7.07	June 26, 3:00 PM
RFCW	IN, OH, WV	10,118	71.84	July 20, 3:00 PM
SRGW	IL, MO	9,453	4.63	July 20, 3:00 PM
CAMX	CA	9,066	2.78	August 17, 2:00 PM
NYUP	NY	9,014	11.83	July 20, 3:00 PM
RFCM	MI	8,976	83.98	July 20, 3:00 PM
NWPP	ID, MT, NV, OR, UT, WA, WY	7,302	3.09	August 10, 3:00 PM
NEWE	CT, ME, MA, NH, RI, VT	3,926	38.05	July 20, 3:00 PM
MROE	WI	3,274	76.97	June 30, 2:00 PM

Table 12: Building Potential for Bill Savings by State From Cooling Measure Energy-Efficiency and Load Shedding

State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)	State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)
Alabama	$2,380	$2,380	**Nebraska**	$1,200	$1,780
		$840			$860
Arizona	$1,180	$2,110	**Nevada**	$560	$1,230
		$140			$ -
Arkansas	$2,280	$2,720	**New Hampshire**	$1,440	$66,090
		$130			$620
California	$1,350	$2,810	**New Jersey**	$1,250	$1,810
		$500			$400
Colorado	$900	$3,190	**New Mexico**	$1,540	$2,870
		$450			$940
Connecticut	$1,810	$2,280	**New York**	$450	$4,020
		$1,550			$130
Delaware	$1,180	$1,180	**North Carolina**	$830	$1,140
		$1,180			$340
District of Columbia	$470	$570	**North Dakota**	$1,110	$1,260
		$360			$800
Florida	$2,020	$2,580	**Ohio**	$1,980	$8,080
		$1,110			$ 30
Georgia	$2,360	$3,600	**Oklahoma**	$1,660	$3,460
		$840			$(140)
Idaho	$460	$640	**Oregon**	$510	$800
		$400			$ -
Illinois	$320	$1,420	**Pennsylvania**	$920	$3,020
		$300			$310
Indiana	$1,360	$3,620	**Rhode Island**	$490	$490
		$(220)			$490
Iowa	$830	$3,650	**South Carolina**	$870	$1,370
		$(410)			$870

State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)	State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)
Kansas	$840	$2,470	**South Dakota**	$920	$1,630
		$(140)			$560
Kentucky	$120	$2,190	**Tennessee**	$840	$3,610
		$(140)			$240
Louisiana	$2,250	$3,170	**Texas**	$2,460	$5,390
		$1,130			$1,050
Maine	$3,940	$3,940	**Utah**	$500	$780
		$1,580			$450
Maryland	$1,370	$3,620	**Vermont**	$1,640	$1,870
		$360			$1,640
Massachusetts	$690	$1,510	**Virginia**	$1,120	$3,120
		$340			$(260)
Michigan	$930	$1,300	**Washington**	$750	$950
		$250			$410
Minnesota	$1,320	$1,590	**West Virginia**	$2,580	$2,580
		$630			$720
Mississippi	$2,580	$3,890	**Wisconsin**	$1,120	$1,950
		$880			$830
Missouri	$510	$1,730	**Wyoming**	$660	$1,210
		$(90)			$10
Montana	$570	$1,150			
		$210			

Note that the retail tariffs associated with the "baseline" and "efficient" scenarios used to calculate the median bill savings shown here can be found in the NREL Data Portal. The tariffs are referred to by their unique tariff codes, which can be used to locate a description of the tariff in the Utility Rate Database.

Table 13: Building Potential for Bulk Power Cost Savings by State From Cooling Energy-Efficiency and Load-Shedding Measure

State	Annual Reduction in Bulk Power Costs (Single Building) ($/yr)	State	Annual Reduction in Bulk Power Costs (Single Building) ($/yr)
Alabama	1,130	**Nebraska**	710
Arizona	600	**Nevada**	230
Arkansas	1,440	**New Hampshire**	210
California	280	**New Jersey**	950
Colorado	350	**New Mexico**	630
Connecticut	210	**New York**	480
Delaware	940	**North Carolina**	1,030
Florida	2,280	**North Dakota**	580
Georgia	1,240	**Ohio**	750
Idaho	220	**Oklahoma**	640
Illinois	480	**Oregon**	220
Indiana	690	**Pennsylvania**	920
Iowa	580	**Rhode Island**	210
Kansas	400	**South Carolina**	1,030
Kentucky	640	**South Dakota**	530
Louisiana	1,880	**Tennessee**	830
Maine	190	**Texas**	1,330
Maryland	970	**Utah**	210
Massachusetts	200	**Vermont**	200
Michigan	640	**Virginia**	630
Minnesota	600	**Washington**	220
Mississippi	2,000	**West Virginia**	510
Missouri	450	**Wisconsin**	570
Montana	250	**Wyoming**	250
Note that although bill savings has a value for the District of Columbia, Cambium does not aggregate results for that region; therefore, it is excluded from estimates for grid impacts.			

Table 14: Building Potential for Grid Emissions Savings by State From Cooling Energy-Efficiency and Load-Shedding Measure

State	Annual Grid CO_2 Emissions Reduction (Single Building) (kg CO_2 per Building/yr)	State	Annual Grid CO_2 Emissions Reduction (Single Building) (kg CO_2 per Building/yr)
Alabama	8,070	**Nebraska**	4,760
Arizona	6,650	**Nevada**	1,770
Arkansas	9,460	**New Hampshire**	290
California	790	**New Jersey**	2,480
Colorado	4,200	**New Mexico**	5,400
Connecticut	620	**New York**	1,260
Delaware	3,310	**North Carolina**	5,570
Florida	9,360	**North Dakota**	7,200
Georgia	7,820	**Ohio**	4,650
Idaho	1,620	**Oklahoma**	6,540
Illinois	3,910	**Oregon**	840
Indiana	4,100	**Pennsylvania**	4,770
Iowa	4,720	**Rhode Island**	410
Kansas	4,370	**South Carolina**	5,090
Kentucky	5,810	**South Dakota**	4,730
Louisiana	7,860	**Tennessee**	4,170
Maine	680	**Texas**	7,650
Maryland	4,460	**Utah**	2,910
Massachusetts	500	**Vermont**	180
Michigan	2,760	**Virginia**	4,100
Minnesota	3,630	**Washington**	720
Mississippi	9,190	**West Virginia**	5,170
Missouri	3,960	**Wisconsin**	3,490
Montana	3,150	**Wyoming**	4,260

Although bill savings has a value for the District of Columbia, Cambium does not aggregate results for that region; therefore, it is excluded from estimates for grid impacts.

A.3 Cooling Energy Efficiency and Precooling

Table 15: Load Impact From Cooling Energy Efficiency and Precooling

EIA EMM Region	States Included	Total Annual Load Reduction per Building (kWh)	Peak Load Reduction (kW)	Peak Timing
ERCT	TX	11,770	(5.66)	August 03, 3:00 PM
SRDA	AR, LA, MS	10,220	(4.55)	July 07, 3:00 PM
FRCC	FL	14,898	(1.28)	July 21, 3:00 PM
SPSO	OK	799	(11.1)	August 02, 3:00 PM
SRSE	AL, GA	1,309	(4.03)	July 07, 3:00 PM
AZMN	AZ, NM	(92)	(8.13)	August 16, 3:00 PM
SRVC	NC, SC, VA	1,454	(5.9)	August 02, 3:00 PM
RFCE	DE, MD, NJ, PA	4144	41.55	July 20, 3:00 PM
SPNO	KS	(1631)	(8.57)	July 20, 3:00 PM
SRCE	KY, TN	(2324)	(9.83)	August 02, 3:00 PM
MROW	IA, MN, NE, ND, SD	2263	(2.46)	June 30, 2:00 PM
RMPA	CO	1085	0.6	June 26, 3:00 PM
RFCW	IN, OH, WV	3310	72.1	July 20, 3:00 PM
SRGW	IL, MO	(1282)	(7.57)	July 20, 3:00 PM
CAMX	CA	(3523)	(7.88)	August 17, 2:00 PM
NYUP	NY	1092	(0.04)	July 20, 3:00 PM
RFCM	MI	2828	83.94	July 20, 3:00 PM
NWPP	ID, MT, NV, OR, UT, WA, WY	838	(35.69)	August 10, 3:00 PM
NEWE	CT, ME, MA, NH, RI, VT	912	38.13	July 20, 3:00 PM
MROE	WI	3274	75.83	June 30, 2:00 PM

Table 16: Building Potential for Bill Savings by State From Cooling Energy Efficiency and Precooling

State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)	State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)
Alabama	$(160)	$(160)	**Nebraska**	$150	$380
		$(1,760)			$(840)
Arizona	$(610)	$(10)	**Nevada**	$(440)	$70
		$(1,210)			$(640)
Arkansas	$(350)	$50	**New Hampshire**	$410	$65,250
		$(1,240)			$140
California	$(1,900)	$(10)	**New Jersey**	$890	$1,140
		$3,120)			$(980)
Colorado	$50	$160	**New Mexico**	$(500)	$510
		$(1,780)			$(2,370)
Connecticut	$560	$1,520	**New York**	$110	$4,050
		$(1,480)			$(9,130)
Delaware	$1,200	$1,200	**North Carolina**	$(990)	$120
		$1,200			$(1,340)
District of Columbia	$70	$380	**North Dakota**	$170	$3,960
		$(230)			$30
Florida	$1,040	$6,770	**Ohio**	$1,060	$6,970
		$(770)			$(1,510)
Georgia	$(590)	$2,060	**Oklahoma**	$(20)	$1,330
		$(1,960)			$(1,100)
Idaho	$(580)	$50	**Oregon**	$(340)	$ -
		$(1,150)			$(890)
Illinois	$70	$670	**Pennsylvania**	$520	$1,280
		$(760)			$(680)
Indiana	$(120)	$1,890	**Rhode Island**	$120	$120
		$(2,750)			$120
Iowa	$30	$1,740	**South Carolina**	$(1,080)	$(970)
		$(2,760)			$(1,290)

State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)	State	Median Annual Customer Bill Savings (Single Building) ($/yr)	Max / Min Annual Customer Bill Savings (Single Building) ($/yr)
Kansas	$(940)	$1,400 $(1,100)	**South Dakota**	$70	$1,610 $(630)
Kentucky	$(760)	$5,070 $(2,430)	**Tennessee**	$(1,450)	$2,230 $(2,410)
Louisiana	$440	$1,060 $(910)	**Texas**	$580	$1,430 $(2,230)
Maine	$3,040	$3,040 $420	**Utah**	$(1,500)	$70 $(1,500)
Maryland	$730	$3,670 $(470)	**Vermont**	$420	$420 $(950)
Massachusetts	$130	$390 $(1,060)	**Virginia**	$(230)	$2,230 $(2,580)
Michigan	$120	$570 $(100)	**Washington**	$(410)	$80 $(890)
Minnesota	$100	$3,960 $60	**West Virginia**	$1,320	$1,720 $(1,420)
Mississippi	$710	$1,250 $(2,010)	**Wisconsin**	$30	$1,530 $(130)
Missouri	$(590)	$330 $(2,500)	**Wyoming**	$ (380)	$120 $(1,500)
Montana	$(460)	$250 $(1,050)			

Note that the retail tariffs associated with the “baseline” and “efficient” scenarios used to calculate the median bill savings shown here can be found in the NREL Data Portal. The tariffs are referred to by their unique tariff codes, which can be used to locate a description of the tariff in the Utility Rate Database.

Table 17: Building Potential for Bulk Power Cost Savings by State From Cooling Energy Efficiency and Precooling

State	Annual Reduction in Bulk Power Costs (Single Building) ($/yr)	State	Annual Reduction in Bulk Power Costs (Single Building) ($/yr)
Alabama	$210	**Nebraska**	$(240)
Arizona	$160	**Nevada**	$80
Arkansas	$190	**New Hampshire**	$100
California	$(60)	**New Jersey**	$540
Colorado	$120	**New Mexico**	$(290)
Connecticut	$90	**New York**	$(750)
Delaware	$540	**North Carolina**	$130
Florida	$1,620	**North Dakota**	$(70)
Georgia	$40	**Ohio**	$420
Idaho	$60	**Oklahoma**	$(1,420)
Illinois	$(850)	**Oregon**	$40
Indiana	$450	**Pennsylvania**	$540
Iowa	$(210)	**Rhode Island**	$100
Kansas	$(1,530)	**South Carolina**	$130
Kentucky	$(770)	**South Dakota**	$70
Louisiana	$840	**Tennessee**	$(150)
Maine	$70	**Texas**	$70
Maryland	$560	**Utah**	$80
Massachusetts	$90	**Vermont**	$90
Michigan	$320	**Virginia**	$(770)
Minnesota	$(80)	**Washington**	$40
Mississippi	$870	**West Virginia**	$340
Missouri	$(850)	**Wisconsin**	$370
Montana	$60	**Wyoming**	$90
Note that although bill savings has a value for the District of Columbia, Cambium does not aggregate results for that region; therefore, it is excluded from estimates for grid impacts.			

Table 18: Building Potential for Grid Emissions Savings by State From Cooling Energy-Efficiency and Precooling Measure

State	Annual Grid CO_2 Emissions Reduction (Single Building) (kg CO_2 per Building/yr)	State	Annual Grid CO_2 Emissions Reduction (Single Building) (kg CO_2 per Building/yr)
Alabama	1,850	**Nebraska**	1,670
Arizona	390	**Nevada**	390
Arkansas	4,210	**New Hampshire**	60
California	10	**New Jersey**	1,020
Colorado	1,260	**New Mexico**	100
Connecticut	260	**New York**	340
Delaware	1,770	**North Carolina**	1,330
Florida	6,560	**North Dakota**	1,510
Georgia	1,710	**Ohio**	2,250
Idaho	440	**Oklahoma**	1,850
Illinois	430	**Oregon**	200
Indiana	1,970	**Pennsylvania**	1,940
Iowa	1,870	**Rhode Island**	100
Kansas	1,030	**South Carolina**	1,480
Kentucky	420	**South Dakota**	1,510
Louisiana	3,850	**Tennessee**	460
Maine	200	**Texas**	4,100
Maryland	1,380	**Utah**	610
Massachusetts	160	**Vermont**	60
Michigan	1,280	**Virginia**	1,130
Minnesota	1,410	**Washington**	150
Mississippi	4,900	**West Virginia**	1,300
Missouri	470	**Wisconsin**	1,490
Montana	950	**Wyoming**	970
Although bill savings has a value for the District of Columbia, Cambium does not aggregate results for that region; therefore, it is excluded from estimates for grid impacts.			

Appendix B. Total Regional Building Footprint for Each Energy Market Module Region

To scale the building load from a total Energy Market Module (EMM) region to a single building, the Scout team provided information on the total building footprint associated with an average large office building (498,588 ft^2) as well as the total regional building footprint associated with each EMM region for large office buildings.

Table 19: Total Regional Building Footprint for Each Energy Market Module Region

EMM Region	Total Regional Building Footprint (million ft^2)	EMM Region	Total Regional Building Footprint (million ft^2)
AZNM	222.52	**RFCE**	1,380.77
CAMX	916.14	**RFCM**	267.59
ERCT	546.94	**RFCW**	1,178.75
FRCC	473.84	**RMPA**	114.22
MROE	80.57	**SPNO**	120.21
MROW	292.66	**SPSO**	202.72
NEWE	407.85	**SRCE**	216.97
NWPP	493.61	**SRDA**	168.96
NYCW	662.25	**SRGW**	209.88
NYLI	163.57	**SRSE**	330.99
NYUP	486.32	**SRVC**	591.12

Appendix C. Energy Market Module Region Mapping to State

Table 20. Energy Market Module Region Mapping to State

State	EMM Region	State	EMM Region
Alabama	SRSE	**Nebraska**	MROW
Arizona	AZNM	**Nevada**	NWPP
Arkansas	SRDA	**New Hampshire**	NEWE
California	CAMX	**New Jersey**	RFCE
Colorado	RMPA	**New Mexico**	AZNM
Connecticut	NEWE	**New York**	NYUP
Delaware	RFCE	**North Carolina**	SRVC
Florida	FRCC	**North Dakota**	MROW
Georgia	SRSE	**Ohio**	RFCW
Idaho	NWPP	**Oklahoma**	SPSO
Illinois	SRGW	**Oregon**	NWPP
Indiana	RFCW	**Pennsylvania**	RFCE
Iowa	MROW	**Rhode Island**	NEWE
Kansas	SPNO	**South Carolina**	SRVC
Kentucky	SRCE	**South Dakota**	MROW
Louisiana	SRDA	**Tennessee**	SRCE
Maine	NEWE	**Texas**	ERCT
Maryland	RFCE	**Utah**	NWPP
Massachusetts	NEWE	**Vermont**	NEWE
Michigan	RFCM	**Virginia**	SRVC
Minnesota	MROW	**Washington**	NWPP
Mississippi	SRDA	**West Virginia**	RFCW
Missouri	SRGW	**Wisconsin**	MROE

Appendix D. Large Office Building Stock by State

ComStock provides information regarding building size and type at a county level. Table 17 shows the count of buildings that match the specifications of the large office building we modeled. New York, California, and Texas have the largest number of large office buildings (characterized as approximately 500,00 ft^2 or larger). Conversely, North Dakota, South Dakota, Wyoming, and Montana, had relatively few large office buildings (< 10), according to the data set.

Table 21: Number of Large Office Buildings (>500,000 sq. ft.)

State	Number of Large Office Buildings*		State	Number of Large Office Buildings*
Alabama	80		**Nebraska**	40
Arizona	90		**Nevada**	20
Arkansas	45		**New Hampshire**	10
California	835		**New Jersey**	275
Colorado	120		**New Mexico**	10
Connecticut	115		**New York**	1,515
Delaware	20		**North Carolina**	220
Florida	415		**North Dakota**	5
Georgia	265		**Ohio**	305
Idaho	35		**Oklahoma**	60
Illinois	645		**Oregon**	70
Indiana	135		**Pennsylvania**	375
Iowa	70		**Rhode Island**	25
Kansas	45		**South Carolina**	65
Kentucky	65		**South Dakota**	5
Louisiana	65		**Tennessee**	205
Maine	25		**Texas**	965
Maryland	225		**Utah**	65
Massachusetts	445		**Vermont**	10
Michigan	210		**Virginia**	315
Minnesota	240		**Washington**	185
Mississippi	25		**West Virginia**	15
Missouri	200		**Wisconsin**	85
Montana	5		**Wyoming**	5

*To develop these estimates for the total number of large office buildings in each state, square footage totals associated with large office buildings by state were taken from ComStock and compared against an assumed average single large office building footage of 498,588 ft^2. Non-integer values indicate large-office buildings with footage that deviates from the assumed average. As many applications are a function of building size (e.g., heating and cooling needs), scaling grid and customer impacts by non-integer values helps to more accurately estimate state-level potential for ECMs to impact customer bills and grid conditions. The results shown here and used throughout the report for scaling individual building impacts to state-level estimated impacts are rounded.

Appendix E. Cambium Limitations

This study leverages the 2020 Cambium data set (Gagnon et al. 2021) to develop estimates for the impact that measures could have on the bulk power system. Although these data can provide useful insights for decision makers when pursuing or developing programs to leverage grid-interactive efficient building technologies, there are important limitations to both the data set and how it was applied in this study. As such, before decision makers use the results of these data, efforts should be made to validate the modeled data against real-world historical data for the region of interest.

Cambium is based on model data that can provide only an estimate of grid conditions in the future at a relatively coarse temporal and geographic resolution—hourly and at the Regional Energy Deployment System™ (ReEDS™) balancing area or state level. Consequently, not all trends in prices, local grid constraints, emissions, etc., that might ultimately inform the impact of a given change in load on the power system can be captured. For bulk power costs, Cambium provides only information on marginal bulk power costs, which areestimates of the costs incurred by the bulk power system by marginal consumption. They are not estimates of retail electricity prices, which typically include cost recovery for other expenses and are often set by ratemaking methods designed to collect target revenue amounts from various customer classes, instead of adhering strictly to marginal cost pricing. Thus, the cost reductions that this study enumerates might differ from what a utility would see in practice, and these should be used only as estimates to changes in costs.

One study compared Cambium data with historical market data, and Lawrence Berkeley National Laboratory modeled future market data to determine the suitability of Cambium data for various analysis efforts (https://emp.lbl.gov/publications/integrating-cambium-marginal-costs). This study found that the directionality of previous Lawrence Berkeley National Laboratory studies was preserved when using Cambium data, although the magnitude of the findings changed. Importantly, the study found that Cambium data might underestimate electricity price variability, and that although annual averages for electricity prices align well, Cambium data might not fully capture diurnal and seasonal price variability. This indicates that Cambium data might be better suited at analyzing the impacts of measures without strong time dependencies (such as energy-efficiency measures) and less well suited for analyzing the impacts with strong time-dependent components (such as demand response measures).

Finally, and analogous to the limitations for estimating customer bill savings, the measures analyzed in this study were "deployed" independently from the Cambium data, with no insight into electricity system pricing or carbon dioxide emissions. In practice, large office buildings might use given energy-efficiency or demand response technologies explicitly to minimize emissions or (if rewarded through intelligent rate design) to minimize consumption during more costly operating hours. To evaluate the full potential of measures, the load pattern changes from the measures would need to be endogenously modeled with information on the marginal grid conditions and retail tariffs. This is particularly important when attempting to aggregate the results from large numbers of large office buildings.

Because in this analysis changes in building load are exogenously compared to marginal grid conditions, it is impossible to measure how large changes in load would ultimately influence the operation of the grid. If a large enough change in load occurred, presumably it could induce a change in the marginal generator (e.g., if a large reduction in load occurred, a natural gas combined-cycle plant might not be dispatched). This would change both the marginal costs and emissions rates and therefore change the impact of the measure.

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