Reducing Grid Costs while Abating Emissions: Opportunities for Flexible Building Loads

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Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-6A40-84828
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Suggested Citation
Zhou, Ella, Elaine Hale, Gord Stephen, and Nikitha Radhakrishnan. 2023. *Reducing Grid Costs while Abating Emissions: Opportunities for Flexible Building Loads*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-84828. https://www.nrel.gov/docs/fy23osti/84828.pdf.

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National Renewable Energy Laboratory
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Golden, CO 80401
303-275-3000 • www.nrel.gov

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This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office. The views expressed herein do not necessarily represent the views of the DOE or the U.S. Government.

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Acknowledgements

This analysis summarizes the Phase 3 results of the U.S. Department of Energy (DOE)'s Flexible Loads project. Funding support for this project is provided by the DOE Building Technologies Office. We especially thank Brian Walker (DOE) and Erika Gupta (formerly DOE) for their support and leadership throughout the project and for this report.

This analysis benefited greatly from thoughtful comments and suggestions from several colleagues who generously reviewed either the entire report or portions of it in draft form, including:

- Elaina Present, Xin Jin, Pieter Gagnon, David Roberts, Mark Ruth, Clayton Barrows, Roderick Jackson, and Jaquelin Cochran (NREL)
- Richard O'Neill (The Advanced Research Projects Agency-Energy)
- Yingchen Zhang (Utilidata)
- Wei Feng (Lawrence Berkeley National Laboratory)

Special thanks go to Mike Meshek for editing and support. Any errors and omissions are the sole responsibility of the authors.

List of Abbreviations and Acronyms

bio	biomass
CC	combined cycle
CO_2e	carbon dioxide equivalent
CSP	concentrating solar power
CT	combustion turbine
DER	distributed energy resource
DPV	distributed photovoltaic
EPA	U.S. Environmental Protection Agency
FERC	Federal Energy Regulatory Commission
GAMS	General Algebraic Modeling System
geo	geothermal
HVAC	heating, ventilation, and air conditioning
ISO-NE	ISO New England
IWG	U.S. Interagency Working Group on the Social Cost of Greenhouse Gases
MISO	Midcontinent Independent System Operator
NG	natural gas
NYISO	New York Independent System Operator
OGS	oil, gas, and steam
PJM	PJM Interconnection
PV	photovoltaics
RC	thermal resistance, thermal capacitance
ReEDS	Regional Energy Deployment System
SC-CO_2	social cost of carbon dioxide
tCO_2	ton of carbon dioxide

Abstract

This study evaluates the value of technology-agnostic, shiftable flexible building loads in modeled 2030 and 2040 U.S. grids for four types of customers under three potential aggregated distributed energy resources programs. The value examined includes monetary value from providing grid services (e.g., energy, capacity, flexibility reserve, regulation reserve, contingency reserve) and from reducing greenhouse gas emissions. By comparing 845,164,800 simulated shifting opportunities, the study finds that the timing of consumption is critical for profit-driven customers. A program that is activated for 30 critical hours of system operation can result in up to \$73/kW per year in revenue for 1 kW of shiftable load. Emission reduction, on the other hand, is best accumulated through a year-round program: shiftable loads can lead to up to 488 kg CO2e/kW carbon reduction per year. The report also provides detailed insights on the trade-off between revenue and emissions, regional variation, short- versus medium- term value, and impacts from various building flexibility parameters, such as shifting window and dissipation.

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1 Introduction

Buildings account for 74% of the electricity use and 40% of the primary energy use in the United States (EIA 2022). As they electrify to reduce economy-wide carbon emissions, buildings can play increasingly important roles in the energy transition by providing a range of grid services (Satchwell et al. 2021), thereby enhancing grid flexibility and renewable energy integration. Recognizing such roles, the Federal Energy Regulatory Commission (FERC) promulgated Order No. 2222, directing the regional grid operators to allow aggregated distributed energy resources (DERs) to participate in the organized wholesale markets. With new market rules, building flexibility could potentially tap into real-time price fluctuations in the wholesale power market. But how much value can different types of building flexibility generate for different types of consumers, and when and where? And what are the carbon emission impacts of building flexibility programs? These are intriguing questions for technology providers, DER aggregators, utilities, regulators, and other stakeholders.

Buildings can contribute to decarbonization through energy efficiency, electrification, and building load flexibility. The interactive impacts of energy efficiency and building demand response on the power system have been studied at a regional scale (Satchwell et al. 2022), and the impact of building electrification and building load flexibility has been investigated (Zhou and Mai 2021). This study focuses on building flexibility as an opportunity for reducing grid costs and abating emissions.

Building flexibility could potentially shed load, shift load, and/or modulate power, thereby providing capacity, energy, and ancillary services to the grid (Satchwell et al. 2021). Several studies quantified the nationwide peak reduction potential of building energy efficiency and/or flexibility (EPRI 2009; Hledik et al. 2019; Langevin et al. 2021). Building energy efficiency and flexibility could also defer transmission and distribution infrastructure upgrades and provide other benefits.

A large body of building flexibility research, however, is at the individual building or building-cluster/community level (Li et al. 2021) and is about developing control strategies for specific equipment or technologies (e.g., HVAC) to provide a limited set of grid services such as ancillary services (Tina, Aneli, and Gagliano 2022; Hao et al. 2014; Pavlak, Henze, and Cushing 2014). Though most of such work focuses on cost savings based on current electricity tariffs (Yoon, Bladick, and Novoselac 2014; Vedullapalli, Hadidi, and Schroeder 2019), recent studies (Miara et al. 2014; Lizana et al. 2018; Huang et al. 2022; Yildiz, Yilmaz, and Celik 2022) have begun to evaluate the environmental and climate benefits from specific building loads. High-geographical resolution, technology-agonistic frameworks are needed that can evaluate the revenue and carbon emission impacts for any load-shiftable building technology, under many possible DER programs, for a variety of grid conditions at the national scale.

The present study examines the value of a unit of technology-agnostic, shiftable, marginal building flexible load that could be sourced from residential or commercial buildings in simulated future grid systems. Such value could be monetary revenue from providing grid services, including capacity, energy, regulation reserve, spinning reserve, and flexibility reserve, or greenhouse gas emission reductions that may or may not be monetized. The study does not cover energy efficiency or electrification, but the latter would greatly increase the building load that could potentially be flexible (Mai et al. 2018). Because different groups of consumers need to be engaged through diverse contracts (He et al. 2013), we compare several possible flexible load product offerings and evaluate the trade-offs between revenue and carbon impacts, filling a critical gap in the literature.

2 Methods

2.1 Future Marketplace for Building Flexibility

With advancements in building equipment, sensing, communication, and control technologies, utilities and DER aggregators may be able to leverage a variety of building resources to provide a broad range of grid services while meeting customers' various goals for participating in demand response. The building resources may include, but are not limited to, heat pumps, phase change material, water heaters, lighting, electronics, and clothes washers and dryers.

For this study, we envision two broad types of customers of building equipment: those driven by profit and those driven by climate change concerns and those who fall in-between (Table 1).

Table 1. Potential Customer Objectives as Considered in this Analysis

Profit-Driven Customer	Moderately Profit-Driven Customer	Moderately Climate-Driven Customer	Climate-Driven Customer
Maximize revenue from providing grid services	Maximize revenue from providing grid services without increasing carbon emissions	Minimize carbon emissions with nonnegative revenue	Minimize carbon emissions

Utilities and DER aggregators may design innovative product offerings that cater to different customers' objectives and usage patterns. Currently, utilities are already offering a variety of demand response programs for sheddable load[1], such as one that pays customers to reduce their load between 11 a.m. and 7 p.m. on a weekday from June to September, no more than 10 times a year (Consumers Energy 2022). Similar program offerings may be designed for shiftable loads. The possible program designs are endless, but we create three potential product offerings (Table 2) for the purpose of estimating their value under various scenarios.

[1] Sheddable load refers to loads that can curtailed for a duration of time. The load reduction will cause no disruption to the customers' quality of life or business function and does not need to be compensated in another time period. For example, outdoor decorative lighting.

Table 2. Potential Building Flexibility Offerings

Shiftable Load Program	Terms
Single Month (daily offer)	*For up to one hour each day in a given month* The timing of the service is undetermined, and the service is not necessarily activated every day of the month. Only the month with the highest revenue or the greatest carbon emission reduction is chosen, unless otherwise noted.
Year-Round (daily offer)	*For up to one hour each day any day during the year* The timing of the service is undetermined, and the service is not necessarily activated every day.
Critical Hours (30 hours/year)	*For up to two hours a day, up to 30 hours in a year* The timing or date of the service is undetermined (i.e., it could be called upon on a spring morning or a summer afternoon).

We design these three potential offerings to provide an overview of building flexibility value when the service has seasonal certainty (Single Month), when it is available daily on an annual basis (Year-Round), and when can cover selected hours of electricity power system needs with day-ahead notice (Critical Hours). The programs can be designed in many ways for different load types. For example, Xcel Energy's Load Management Standard Offer Program offers commercial customers incentives for load shedding with a maximum event duration of four hours (Xcel Energy 2022). For our shiftable load programs, we choose relatively short duration requirements to make it easy for different loads to participate. The results, therefore, could be interpreted as a lower bound of the building flexibility value. We select 30 hours for the Critical Hours program for two reasons:

1. This is similar to the number of hours available under the Critical Month offering, making them more comparable.
2. The number of hours requiring sheddable demand response events is about 20-30 hours currently and more hours will be needed in the future (Hledik et al. 2022), so the 30-hour requirement would be likely to attract similar participation levels to those seen in today's programs.

2.2 Flexible Building Loads and Grid Modeling

For the present study, we developed a mixed-integer linear program to dispatch a marginal unit of shiftable building load against electricity prices or carbon emission rates. The model was written in the General Algebraic Modeling System (GAMS) version 24.9 and solved with the IBM ILOG CPLEX Optimizer. We examined a marginal 1 kW of building energy consumption at a given hour h that could be shifted within 24 hours. Each hour of the year and each region was evaluated separately to provide disaggregated results. All results reported here are interpreted with a unit of per kW-day or per kWh-day, depending on whether it is providing capacity or energy. Details of the model are documented by Zhou, Hale, and Present (2022), and we describe some key features of the model in this section.

The model can switch between two objective functions: maximizing revenue from providing grid services and minimizing carbon emissions; it can also constrain emission reduction or revenue to be nonnegative. The customer types described in Table 1 are mapped accordingly to the objectives and constraints, which are then enforced per event, that is, for each potential daily shift of 1 kW of shiftable load at hour h.

The shiftable building load is characterized by the following parameters, in addition to the original time and location of consumption:

1. **Shifting Window:** the range of hours to which the consumption could be shifted. For example, a shifting window of [-4, +4] means the load is allowed to shift to any time from 4 hours earlier to 4 hours later than the original time of use.
2. **Shifting Efficiency:** the conversion efficiency from electricity to energy service after the consumption is shifted relative to the conversion efficiency at the original hour of usage. *Nota bene:* this is not the characteristics of the equipment itself that are changing, but the conditions in which the equipment is operating change the efficiency of operation. For example, an air conditioner requires less electricity to cool a room to the same temperature if it is activated when it is cooler outside as compared to when it is hotter outside; therefore precooling (e.g., shifting air conditioner usage from noon to morning) result in a shifting efficiency of greater than 1.
3. **Dissipation Rate:** the rate at which the energy service degrades over time. For example, the hot water in a water heater, without additional heating, will cool at a rate proportional to 1/RC, where R is thermal resistance and C is thermal capacitance.
4. **Power Capacity Constraint:** the equipment rating that limits the maximum power draw of the appliance or technology.

We use these generic flexibility parameters to capture the main features of any shiftable building technology, residential or commercial, so that technology providers, utilities, and DER aggregators can gain insights on the potential value of building flexibility services based on the building load's technical capability and customers' willingness to participate.[2] For example, schedulable loads such as dishwashers and clothes dryers could be seen as having a shifting efficiency of 1 and a dissipation rate of 0, and they may have different shifting windows based on the customers' preference; whereas HVAC and water heating end uses are subject to some dissipation and could have non-unity shifting efficiencies.

We use the electricity prices and short-run marginal greenhouse gas emission rate (in CO_2 equivalent, or CO2e) from two grid scenarios in the *2021 Standard Scenarios Report* (W. Cole et al. 2021), processed through Cambium (Gagnon et al. 2021), as inputs to the shiftable building load dispatch model:

- The LowCarbon grid scenario (referred to as the Mid-Case 95% by2035 in the *Standard Scenarios*) assumes a 95% CO_2 emission reduction in the nation's power sector by 2035 compared to 2005 levels.

[2] In addition to consideration for comfort levels, another consideration is that providing some ancillary services (e.g., using HVAC to provide fast regulation reserves) might cause wear and tear of the equipment (Hao et al. 2014). Even though modern dispatching algorithms intentionally ramp rapidly moving signals, the consumers, and thereby DER aggregators, may still be unwilling to use their equipment for such services despite having the technical capability to do so.

- The MidCase grid scenario (referred to as the Mid-Case in the *Standard Scenarios*) uses default or median assumptions in the *Standard Scenarios*. It serves as a counterfactual scenario in which no new renewable or carbon policies is adopted beyond those in place as of June 2021.

We model electric power systems in both 2030 and 2040 (Figure 1) under both grid scenarios to compare the near- and medium-term opportunities for building flexibility. For grid service revenue, we consider revenues from providing capacity, energy, regulation reserve, flexibility reserve, and contingency reserve. Capacity price represents the cost of capital investment needed to meet the next incremental load; energy price represents the operating cost of servicing the next incremental load; and the three types of ancillary service prices represent the cost of maintaining the system balance at different timescales (Zhou et al. 2022). For carbon emissions, we consider the short-run marginal CO_2 equivalent rate that reflects the global warming potential from carbon dioxide, methane, and nitrous oxides from a marginal unit of load on power system *operation*, because we do not assume the building flexibility would provide a *consistent* change in load. Details of these input metrics are documented by Gagnon et al. (2021).

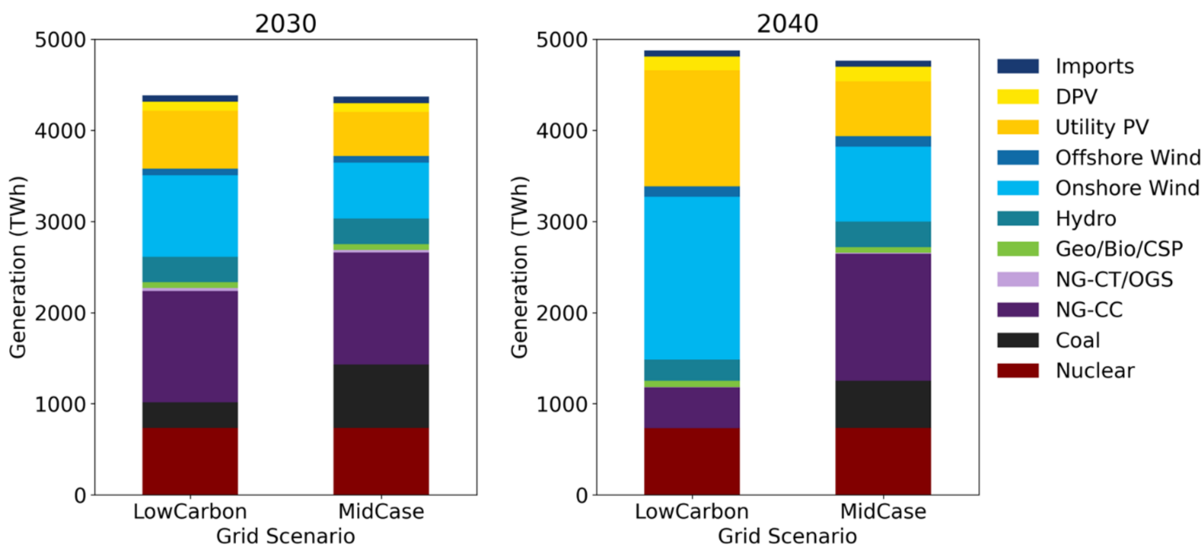

Figure 1. Generation mix of the four simulated grid scenarios: LowCarbon 2030, MidCase 2030, LowCarbon 2040, and MidCase 2040

DPV = distributed photovoltaic; PV = photovoltaic; geo = geothermal; bio = biomass; CSP = concentrating solar power; NG = natural gas; CT = combustion turbine; OGS = oil, gas, and steam; CC = combined cycle

For each customer type, original hour of usage, and simulated balancing area, we examine a full set of 180 scenarios (Table 3). The model does not allow shifting energy to later in the day when the dissipation rate is more than 0 because the model needs to ensure that the same level of energy service is provided within the given window. In total, we examine 845,164,800 simulated shifting opportunities. We define the reference case to have a shifting window [-12, +11], shifting efficiency of 1.0, and dissipation rate of 0.0 (marked in bold in Table 3).

Table 3. Scenario Table [a]

Grid Scenario	Shifting Window (hour)	Shifting Efficiency	Dissipation Rate	Power Capacity Limit (kW)
One of: • LowCarbon 2030 • LowCarbon 2040 • MidCase 2030 • MidCase 2040	One of: • [-1, +0] • [-1, +1][b] • [-4, +0] • [-4, +4][b] • [-12, +0] • **[-12, +11][b]**	One of: • 0.75 • **1.0** • 1.25	One of: • **0.0** • 0.005 • 0.05 • 0.5	**64**

[a] The number of rows in each column is multiplied to obtain a set of 180 scenarios, with one exception: two-sided shifting windows are paired with only one dissipation rate (0.0). Parameters marked in bold define the reference case.

[b] Only allowed for scenarios with a dissipation rate of 0

2.3 Social Cost of Carbon Emissions

We separate the four types of customers (Table 1) to avoid implementing a specific cost of carbon in the optimized dispatch, because the cost assumption we use would have a significant impact on the results. Many researchers have attempted to quantify the monetized value of damages caused by an incremental unit of CO_2 emissions, which is known as the social cost of carbon dioxide (SC-CO_2). The U.S. Interagency Working Group on the Social Cost of Greenhouse Gases (IWG) estimates that the SC-CO_2 in 2020 averaged about $51/kW (in 2020 dollars) per ton of carbon dioxide (tCO_2) under a 3% discount rate and $76/kW under a 2.5% discount rate (IWG 2021). This is significantly lower than other estimates of mean SC-CO_2 of $185/kW per t$CO_2$ ($44–$413/kW per tCO_2: 5%–95% range) when explicitly accounting for the uncertainty in future demographic, economic, and emissions' projections (Rennert et al. 2022). Also, the U.S. Environmental Protection Agency (EPA) is updating its SC-CO_2 estimates following the recommendations from the National Academies of Sciences, Engineering and Medicine (National Academies 2017), but only an external review version of the estimates is available at this time (EPA 2022). We use the SC-CO_2 from several peer-reviewed sources[3] (IWG 2021; Ricke et al. 2018; Pindyck 2016; Bressler 2021; Cai, Lenton, and Lontzek 2016; EPA 2022) to provide a range of the gross value of building flexibility programs when accounting for the social cost of carbon (Figure 5). The SO-CO_2 estimates used in the analysis are listed in Appendix A.

[3] We use the mean estimate for SC-CO_2 at a discount rate of 2.5% from each study where one is available, and we convert all values to 2020 U.S. dollars. The discount rate has a big impact on the SC-CO_2 (Pizer et al. 2014; Adler et al. 2017). Using a higher discount rate would result in a lower SC-CO2 and would thereby reduce the value of programs that lead to higher carbon emission savings as opposed to monetary revenue from grid services. Due to scope limitations, we do not evaluate SC-CO_2 estimates under alternative discount rates.

3 Caveats

Our study scope is limited in several ways. First, we only examine the value of building flexibility from providing grid services and reducing emissions; we do not assess the cost of implementation, which may include equipment cost, energy management system cost, administrative cost, customer acquisition cost, and other costs.

Second, our study is based on simulated future electricity prices and greenhouse gas emission rates. The Regional Energy Deployment System (ReEDS) model has been calibrated with historical capacity builds (W. J. Cole and Vincent 2019), but the simulated prices tend to be much less volatile than real-world prices. This means we are likely to underestimate the potential revenue for building flexibility. Nevertheless, real-time prices are seldom passed down to end users even though proposals to introduce dynamic energy and capacity costs reflecting real-time grid needs have been discussed in some jurisdictions (Madduri et al. 2022). Real-time greenhouse gas emission rates from the power grid are even more elusive to the public. To address this, the Infrastructure Investment and Jobs Act directs the U.S. Energy Information Administration to report average and marginal greenhouse gas emissions per megawatt-hour of electricity for each balancing authority. The present study values the resulting carbon emission impacts from electricity system operational changes when the end users are responding to price or emission signals if and when such information is available in real time. Another caveat here is that, due to the sporadic nature of the flexible load activation in the Critical Hours program, we only evaluate the short-run marginal emission impacts. This does not include the impacts from the structural changes in the power system, but such impacts are possible with sustained changes in load.

Third, we acknowledge having limited insights into future grid development, technology evolution, and socioeconomic conditions. This is why we take a scenario approach and try to capture a range of possibilities; however, the number of scenarios we evaluate is constrained by resources. The simulated building parameters (Table 3) were determined through discussions with building equipment and grid experts; they by no means represent the full range of possible building flexibility features. In reality, some of the parameters, such as shifting efficiency, may be correlated with outdoor temperature, but our modeled scenario is based on a single weather year (2012). We simplified these parameters to reduce computational burden and to simplify interpretation for existing or new technologies and equipment. Analyzing the value of building technologies based on multiple weather years with projections of future climate impacts could be a direction for future research. We also acknowledge that a wide variety of methods exist for calculating the social cost of carbon (Palmer et al. 2022). We select estimates from several prominent studies to provide a range of potential monetary value from building flexibility when the social of cost of carbon is considered.

Despite these limitations, the present work provides estimates of building flexibility's grid service revenue and greenhouse gas emission impacts under various program offerings and for different customers in near- and medium-term grids for the contiguous United States. The insights could inform regulators, utilities, DER aggregators, and technology providers on setting cost target for building flexibility, designing flexible load programs, and inform end users on the impacts of their participation in such programs.

4 Results

We explore three themes in our results: (1) the trade-offs between revenue and carbon emission reduction, (2) the sensitivity of building flexibility value to various parameters, and (3) regional variations. All results are for 1 kW of marginal, flexible building load at a given consumption hour that could be shifted within a 24-hour period, and all revenues are reported in real terms in 2020 U.S. dollars.

4.1 The Interplay of Revenue and Emissions

The grid service revenue and carbon emission impact of building flexible loads vary greatly by grid scenarios, regions, hours of usage, and building flexibility parameters. We start by examining the trade-offs between revenue and emission impact. Table 4 and 5 show the full range of grid service revenue and carbon emission impact, respectively, across all hours, regions, and building flexibility parameters for LowCarbon 2030. Results for other grid scenarios are summarized in Appendix B.

Table 4. Range of Grid Service Revenue in LowCarbon 2030

Revenue ($/kW)	**Critical Hours**	**Single Month**	**Year-Round**
Profit-Driven	39 to 41	15 to 21	10 to 54
Moderately Profit-Driven	11 to 41	5 to 21	1 to 54
Moderately Climate-Driven	1 to 7	0 to 8	5 to 27
Climate-Driven	-15 to 7	-13 to 7	-63 to 21

Table 5. Range of Carbon Emissions in LowCarbon 2030[a]

Emissions (kg CO2e/kW)	**Critical Hours**	**Single Month**	**Year-Round**
Profit-Driven	-32 to 213	-33 to 99	-33 to 96
Moderately Profit-Driven	-34 to 0	-33 to -2	-33 to -11
Moderately Climate-Driven	-50 to -13	-45 to -3	-470 to -13
Climate-Driven	-50 to -14	-45 to -3	-470 to -15

[a] Negative emission numbers indicate carbon emission reduction. Positive emission numbers indicate emission increase.

4.1.1 Comparison of Shiftable Load Programs

The results demonstrate that the Profit-Driven customer could increase carbon emissions, particularly under Critical Hours and Single Month programs. As Figure 2 shows, when unconstrained, many but not all Critical Hours programs for the Profit-Driven customer can increase carbon emissions. In the extreme cases, with only 30 hours of service per year from 1 kWh of shiftable building load, the Critical Hours program can achieve up to $73/kW in revenue, but it can also increase emissions by up to 332 kg CO_2e/kW. The mixed impacts on carbon emissions are corroborated under several cost-optimizing grid integration studies of shiftable demand response (Hale, Stoll, and Novacheck 2018; Fleschutz et al. 2021; Zhou and Mai 2021). Whether demand flexibility increases or decreases carbon emissions is contingent on the overall system build-out and fuel prices. For example, when the coal price is low, demand flexibility that reduces consumption at system net load peak hours and increases consumption during low-load hours would enable inflexible coal generation to displace natural gas generation (Hale, Stoll, and Novacheck 2018; Fleschutz et al. 2021; Zhou and Mai 2021), similar to what has been observed for storage (Denholm et al. 2013). The pendulum tends to swing the other direction as the power system decarbonizes. Considering all parameter combinations and regions, 40% of the Critical Hours programs induce emission reduction in MidCase 2030. This number grows to 48% in the LowCarbon 2030 scenario and 56% in the LowCarbon 2040 case. Across all grid scenarios, regions, and building flexibility parameters, roughly 28% of the value is lost in the Critical Hours program for the Moderately Profit-Driven customer, compared to the Profit-Driven customer.

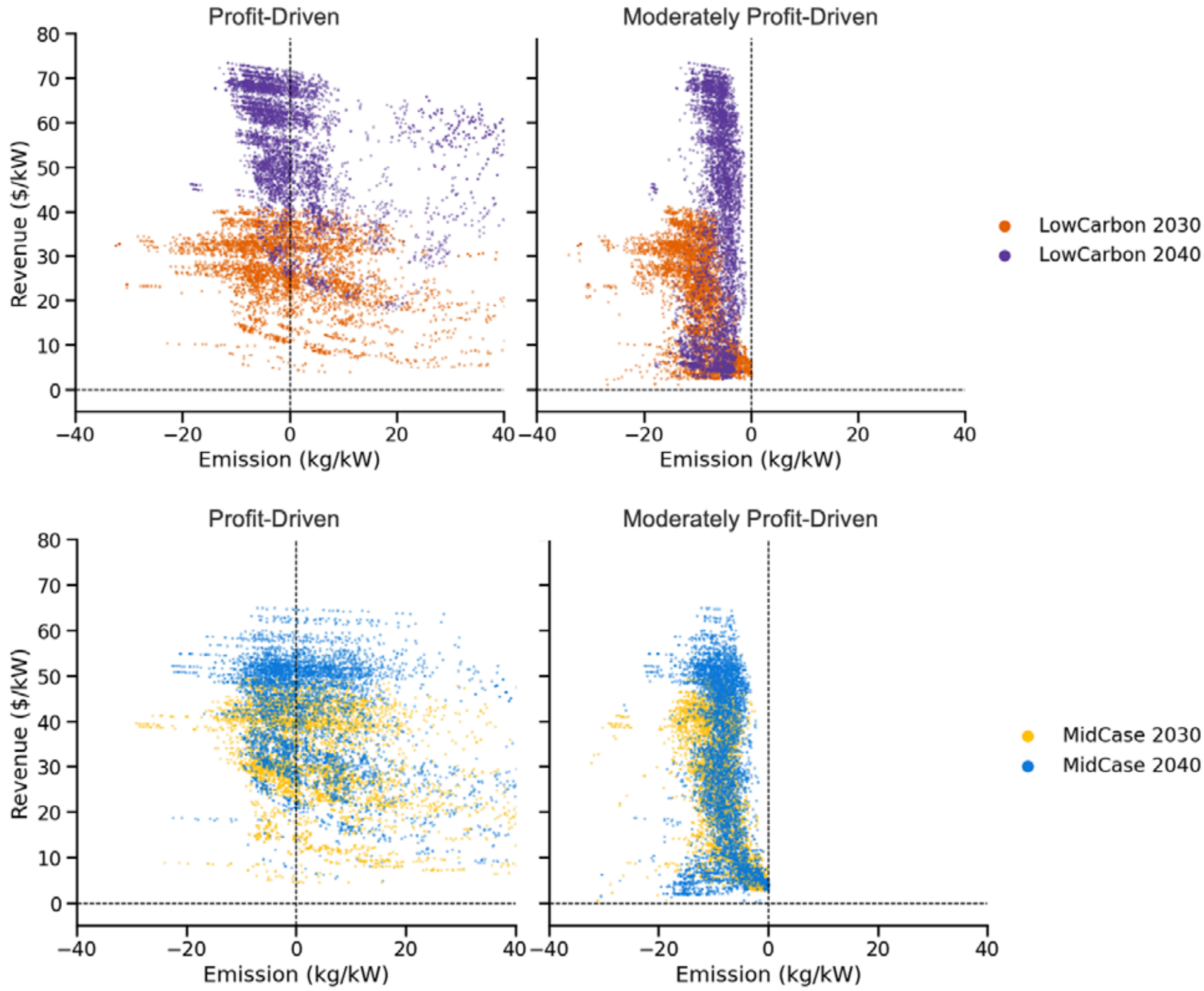

Figure 2. Revenue and emission impacts of the Critical Hours programs for the Profit-Driven customer, across all examined parameters (shifting window, shifting efficiency, dissipation rate) and regions, by grid scenario and customer type

Negative emission numbers indicate carbon emission reduction. Positive emission numbers indicate emission increase. The plots zoom in to make most of the data points visible, but they are not capturing the max values of the programs.

The Year-Round program has a much higher probability of delivering carbon emission reductions, even for the Profit-Driven customer (Figure 3). Because emission reduction opportunities are spread out throughout the year, the Year-Round program captures more hours for energy arbitrage by shifting consumption to high renewable energy generation, low electricity price, and low carbon emission hours. This is in contrast to the Critical Hours program, which is aimed at capturing up to thirty ultra-high capacity price hours (see Section 4.2.1). This result is especially prominent under the LowCarbon scenarios. Across all simulated parameters and regions, 89% of the Year-Round programs in the LowCarbon 2030 scenario (and 100% under the reference case) can reduce carbon emissions, contributing up to 327 kg CO2e/kW of emission reduction, compared to 48% of the Critical Hours programs and 60% of the Single Month programs in the same grid scenario. The Year-Round program for the

Moderately Profit-Driven customer sees 24% revenue reduction compared to the Profit-Driven customer, which is less revenue decrease than that in the Critical Hours program.

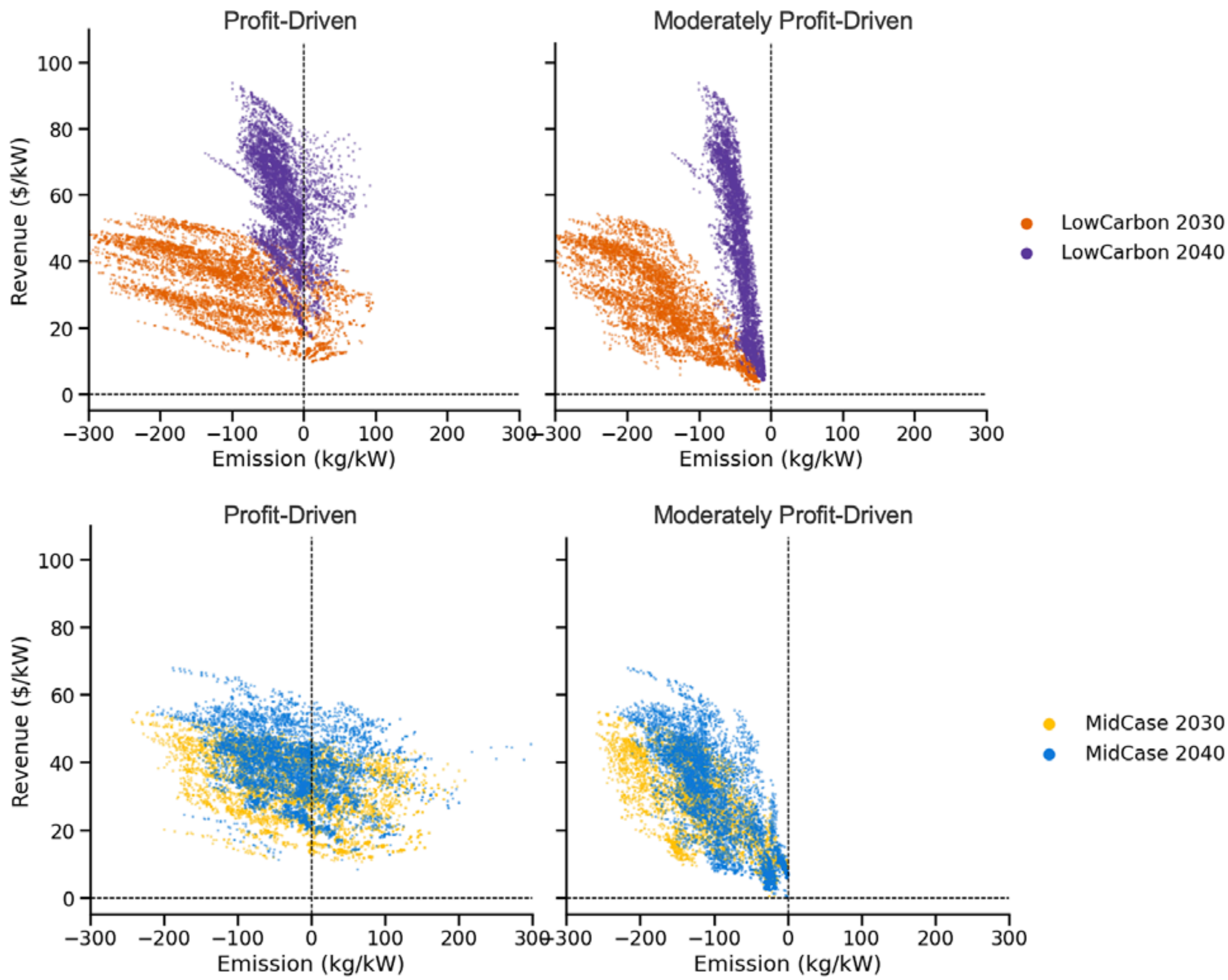

Figure 3. Revenue and emission impacts of the Year-Round program for the Profit-Driven customer, across all examined parameters (shifting window, shifting efficiency, dissipation rate) and regions, by grid scenario and customer type

Negative emission numbers indicate carbon emission reduction.

For the Climate-Driven customer, the Year-Round program could often yield a positive revenue, especially under the LowCarbon scenarios (Figure 4). It could result in up to 470 kg CO2e/kW of emission reduction and up to $21/kW in revenue in the LowCarbon 2030 scenario, with 75% of the programs resulting in positive revenue. A Year-Round program in the MidCase 2030 can induce up to 488 kg CO2e/kW carbon reduction, but the resulting revenue is less than that under the LowCarbon scenarios. As expected, the opportunities for emission reduction are diminished in the LowCarbon 2040 scenario as nonfossil fuel generation reaches around 90% of national annual generation. Still, in the LowCarbon 2040 scenario, the Year-Round program can result in up to 184 kg/kW CO2e of emission reduction and up to $57/kW in revenue. On average, across all scenarios, regions, and simulated parameters, the Moderately Climate-Driven customer sees 23% less emission reduction under the Year-Round program compared to the Climate-Driven customer, gaining almost twice the revenue (i.e., \$11/kW for the Moderately Climate-Driven customer and \$6/kW for the Climate-Driven customer).

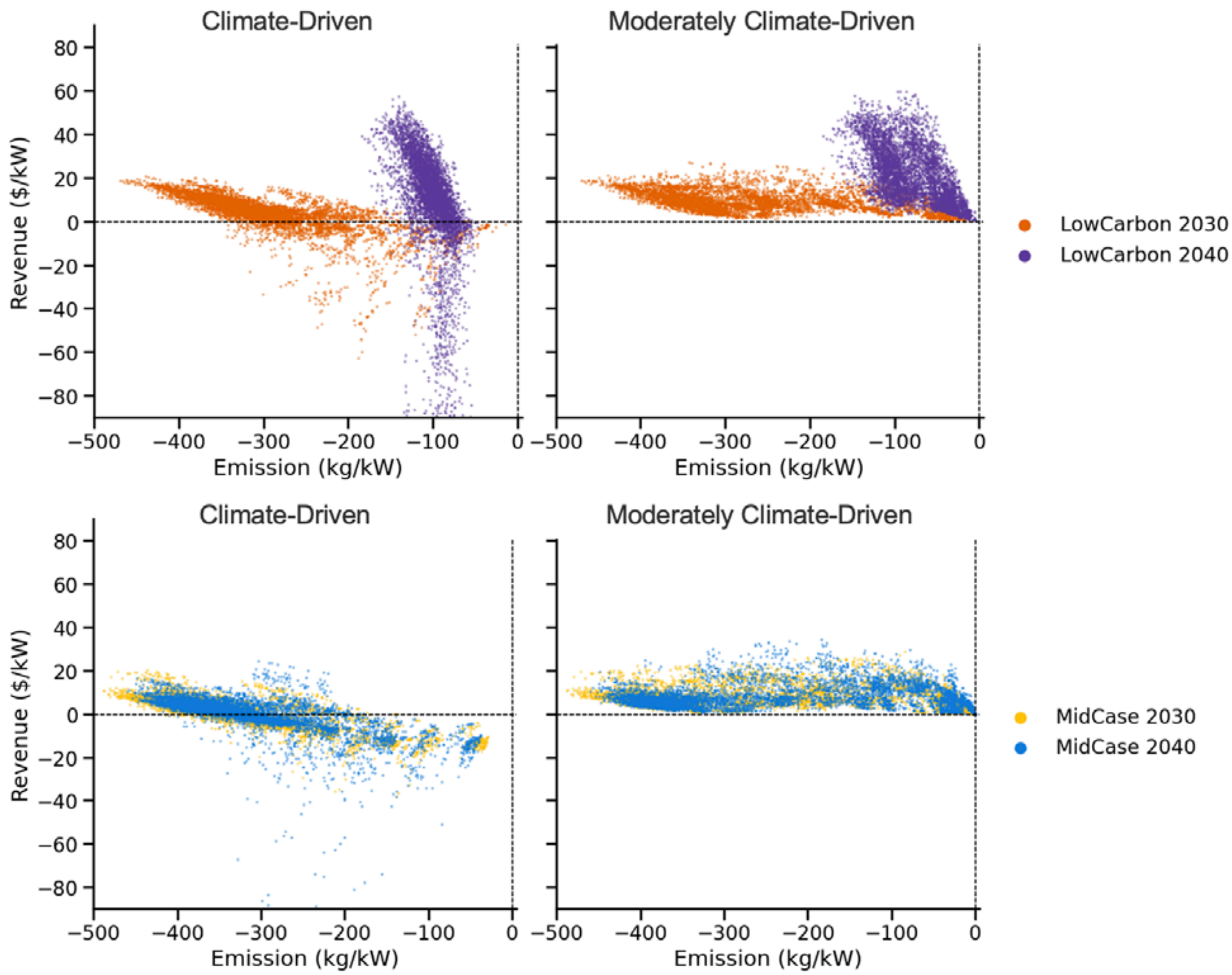

Figure 4. Revenue and emission impacts of the Year-Round program for the Climate-Driven customer, across all examined parameters (shifting window, shifting efficiency, dissipation rate) and regions, by grid scenario and customer type

Negative emission numbers indicate carbon emission reduction.

These results indicate that using a Year-Round program in the near term to minimize carbon emissions and using a Critical Hours program in the future to maximize revenue could have the greatest emission and revenue benefits. As expected, the Single Month program sees less revenue and emission reduction than the Critical Hours program for roughly the same number of hours of service.

4.1.2 Social Cost of Carbon Emissions

For the Climate-Driven customer and the Moderately Climate-Driven customer, the SC-CO_2 estimate has a huge impact on the overall monetary value of the program. For example, the Year-Round program for the Climate-Driven customer with reference flexibility (i.e., efficiency = 1, dissipation rate = 0, window = [-12, +11]) in the LowCarbon scenario 2030 across all regions is

$42–$51/kW (interquartile range) using the lowest estimate from IWG (2021) and $160–$184/kW using the highest estimate from Ricke et al. (2018). Under the same conditions, the grid service revenues alone are only $5–$17/kW (interquartile range). Thus, adding the monetized value of carbon emission reductions to grid service revenue likely better reflects the value of this type of program to people who prefer to minimize emissions.

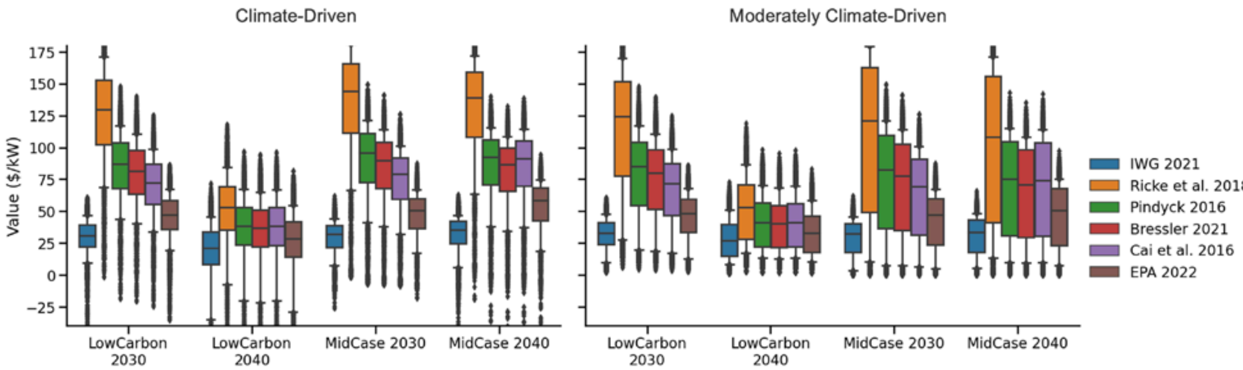

Figure 5. Monetary value of Year-Round programs for the Climate-Driven customer and Moderately Climate-Driven customer when accounting for grid revenues and the social cost of carbon emissions, by grid scenario and sources of SC-CO_2 estimates

The plot contains the total annual value of Year-Round programs for all examined combinations of parameters and in each region. Whiskers extend from 10% to 90% of the plotted data.

The SC-CO_2 assumptions do not have an unusually large impact on the programs for the Profit-Driven customer because carbon emissions account for a smaller portion of their value: the maximum emission reductions for the Profit-Driven customer and the Moderately Profit-Driven customer are only 22kg CO2e/kW and 33kg CO2e/kW under the Critical Hours and the Single Month programs respectively. But even a moderate estimate of SC-CO_2 could tip the scales in some circumstances. Using EPA 2022's estimates, 1.4% of the Critical Hours programs for the Profit-Driven customer would lead to a negative overall societal value. Nevertheless, if the SC-CO_2 is not reflected in electricity prices or through some type of carbon credit mechanism, the Profit-Driven customer has no incentive to make decisions that account for the value of emission reductions, estimates for which continue to be updated and have been increasing.

4.2 Sensitivity to Building Flexibility Parameters

4.2.1 Time of Service

For the Profit-Driven customer, the original time of service—the hour of the day and the season of the year —is critical for maximizing revenue when all else is equal. On a diurnal scale, building load flexibility during the evening hours tends to be more lucrative than during daytime hours (e.g., 10:00–14:00) (Figure 6). On a seasonal scale, the summer months tend to return higher revenue than the other months in regions that are summer peaking. Across all scenarios and flexibility parameters, 88% of the 134 simulated balancing areas have the highest revenue in July or August. This temporal pattern reflects the high energy and capacity prices due to high net load in these periods. Systems in different climate zones have different times when building flexibility is most valuable. As building loads electrify, the adoption of heat pumps in colder climates could drive more systems to be winter-peaking or dual-peaking (Mai et al. 2018), thereby increasing the likelihood that flexible building loads can obtain higher revenue in the winter months. Such regional variations are discussed in detail in Section 5.3.

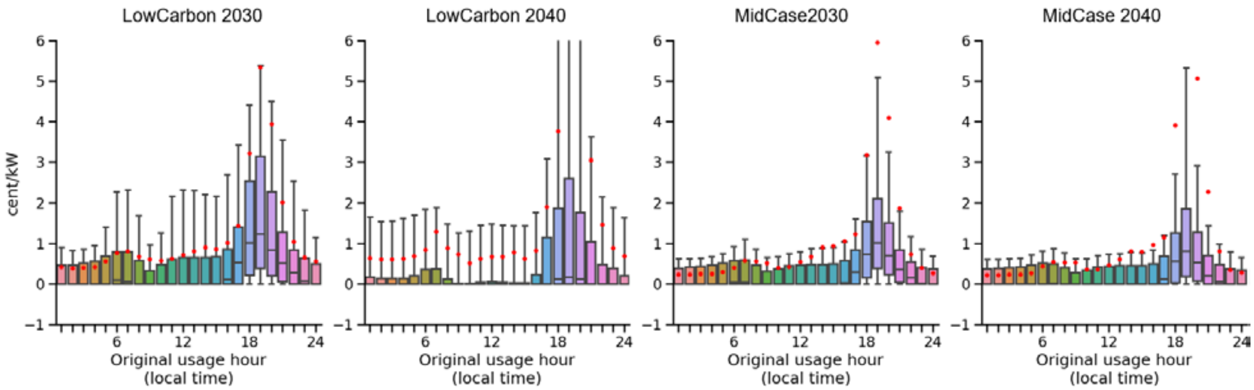

Figure 6. Hourly grid service revenue (cent/kWh) by the original usage hour in local time (x axis) and by grid scenario (subplot) for the Profit-Driven customer (maximize grid service revenue)

The plot includes results across all days of the year, regions, and examined parameters.
The whiskers extend from 10% to 90% of the plotted data. The red dots indicate the means.

Consumers, however, may not want to shift their energy consumption every day. The Critical Hours program is effective capturing a high amount of revenue with only 30 hours of service annually (Figure 2). The program can result in $10–$41/kW (interquartile range) and $45–$73/kW of annual revenue under the reference case in the LowCarbon 2030 and LowCarbon 2040 scenarios, respectively, compared to $11–$15/kW and $18–$29/kW under the Single Month program and $22–$54/kW and $37–$92/kW under the Year-Round program.

The high value of the Critical Hours program is primarily driven by the few hours of the year with extremely high capacity cost. The capacity cost simulated in ReEDS[4] is derived from the shadow price of the planning reserve margin. It reflects the long-run cost of additional capital investment in the power system needed to meet the increase in demand plus the reserve margin. The simulated capacity prices are generally lower than what has been observed in the U.S. centralized capacity markets operated by ISO New England (ISO-NE), Midcontinent Independent System Operator (MISO), New York Independent System Operator (NYISO) and PJM Interconnection (PJM). This is partly because ReEDS evaluates a broader range of supply options, whereas the market capacity prices are typically based only on the net cost of new entry, which is set by the cost of a natural gas-fired combustion turbine (Aagaard and Kleit 2022). Real-world capacity market auctions take place between one month (NYISO) and three years (PJM, ISO-NE) before the relevant commitment period, and the capacity has a long delivery period (12-month in ISO-NE, MISO, and PJM, 6-month for winter and 6-month for summer in NYISO). These markets do not publish any hourly prices for capacity. The weighted average capacity price for these four markets is around $43/MW-day to 583/MW-day and the hourly penalties for nonperformance are in the range of $2,000//MWh– $4,000/MWh (ISO-NE and PJM) (Byers, Levin, and Botterud 2018). But only a few hours in a year qualify as

[4] ReEDS finds the least-cost option among (1) the net cost of new entry (net cost of new entry) for generation, (2) new transmission capacity, and (3) delayed retirement. Cambium then allocates the cost of the selected option to the individual hours that pass the threshold for the 101 highest net-load hour or 95% of the reliability assessment zone's annual peak net load, whichever is lower (Gagnon et al. 2021).

emergency events when the committed capacity would be subject to penalties for nonperformance or underperformance. For example, 42 hours across 8 days qualified between 2011 and 2014 as emergency events for PJM (Hunger, Plewes, and Kwok 2017). Our simulated capacity prices capture these features as they remain at zero for about 98% of the time and up to around $6,500/MW-hour during the peak net load hours. As a result, our estimate for the Critical Hours program reflects the value of building flexibility to the grid during the few hours when the grid is strained for electricity supply, but the exact magnitude of and how these price signals could be passed down to the demand side depends on the local market structure.

4.2.2 Shifting Efficiency, Dissipation Rate, and Shifting Window

As expected, higher shifting efficiency, lower dissipation rates, and larger shifting windows lead to higher grid service revenue and greater emission reductions. Our results add some nuances to this understanding. When the dissipation rate is high, more energy is needed to provide the same service, as noted in published research showing significantly higher power payback following a demand response event in dwellings of low thermal inertia (Zhang, Good, and Mancarella 2019). This effect would cause emission increases in some of the profit-driven programs that would otherwise result in emission reductions. It indicates that measures to minimize dissipation, such as building envelope efficiency upgrades (e.g., attic, wall, and floor insulation), can both generate efficiency savings during normal operation and improve the economics and carbon emission reduction potential during load shifting events.

For flexible building load that is shiftable within a 24-hour period, the results show that increases in the shifting window do not necessarily produce commensurate increases in revenues or emission reductions, regardless of grid scenario or shiftable load program type. Taking the Critical Hours program for the Profit-Driven customer as an example (Figure 7), customers can obtain noticeably higher revenue when they provide 4-hour shifting than when they provide 1-hour or 1-hour-each-direction shifting. But the incremental increase in revenue with more than 4 hours of shifting is limited. This indicates that for the near- to medium- term, utilities, technology providers, and DER aggregators may not necessarily have to secure building resources that can provide longer-duration shifting. Building loads that can be shifted for a short period ([-4, +0] hours compared to [-12, +12] hours) can already harness most of the grid service revenue and carbon emission reduction potential.

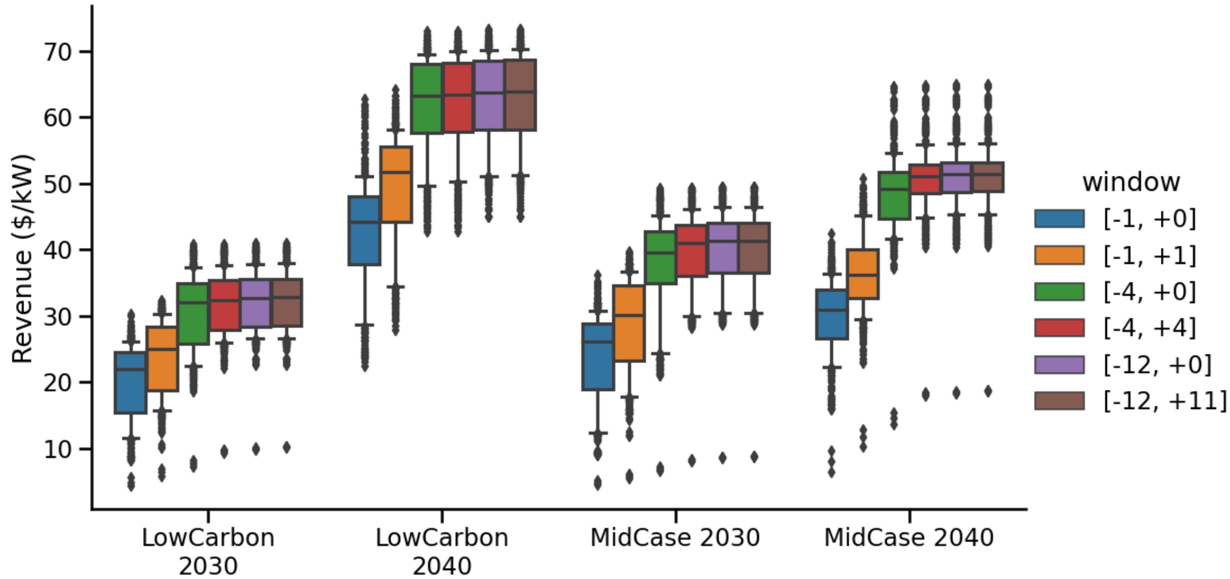

Figure 7. Grid service revenue for the Critical Hours program for profit seekers, dissipation rate=0, across all regions and efficiency, by grid scenario and by shifting window size

Whiskers extend from 10% to 90% of the plotted data. Dissipation rate is limited to 0 in this figure because only simulations where dissipation rate=0 is allowed to shift to either direction, making the number of results for the different windows comparable.

4.3 Regional Variations

The simulation results show that all regions can obtain substantial grid service revenue or carbon emission reductions under appropriate programs (Figures 2, 3, 4). But the timing of service and the emissions impact when optimizing for profit are highly dependent on the region. For example, a Single Month program in July would return the highest revenue for most regions in the contiguous United States, except in parts of California, Arizona, New Mexico, and Texas, where August would be most profitable, and except in Washington and Oregon, where January would be most profitable (Figure 8 left panel). The simulation results also show that typically it is more profitable to shift away from the evening peak hour (Figure 6), but in Washington, for example, it is often more profitable to shift away from the morning peak hour. This indicates that utilities and DER aggregators should design their programs based on the local load and system characteristics. As winter net peak loads start to rise due to heat pump adoption, it is likely that a Single Month program would be activated during the winter in more regions.

The carbon emission impacts when maximizing revenue for the Profit-Driven customer also vary by region and by program. A Single Month program in July results in emission reductions in most regions in MidCase 2030 with reference flexibility, but it would increase carbon emissions in parts of Washington, Oregon, and Montana (Figure 8 right panel). The Critical Hours program would deliver much higher revenue for the Profit-Driven customer than the Single Month program under the same conditions, but it would also cause emission increases in even more regions.

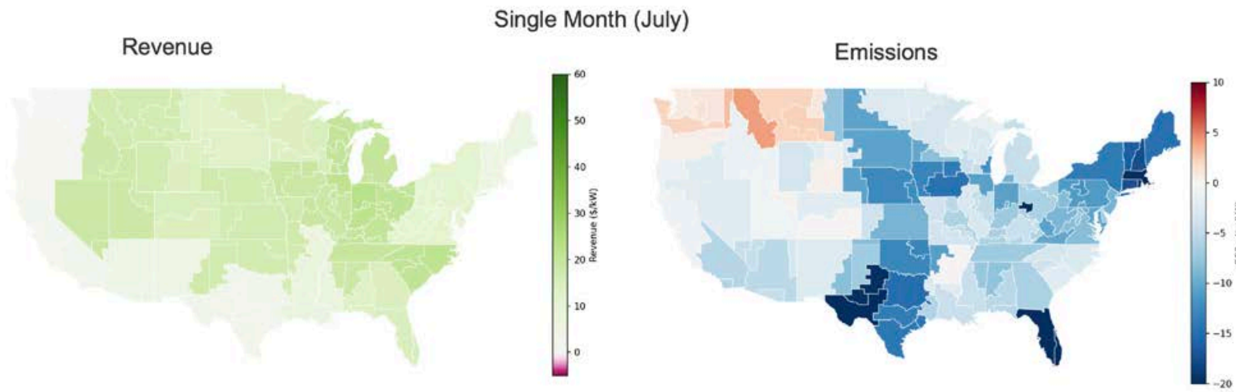

Figure 8. Revenue ($/kW) and carbon emissions (kg CO2e/kW) impacts from building flexibility in a Single Month (July) program for the Profit-Driven customer with reference flexibility (shifting efficiency = 1, dissipation rate = 0, window = [-12, +11]) in MidCase 2030

In contrast, both Critical Hours and Year-Round programs for the Climate-Driven customer deliver positive revenue in all regions with reference flexibility in all grid scenarios, and only the Single Month program leads to a very limited negative revenue in a few areas. As discussed in Section 5.1.1, the objectives for revenue and carbon emissions reduction are better aligned as the grid decarbonizes. In the LowCarbon 2040 scenario for example, even the Critical Hours program for the Profit-Driven customer with reference flexibility results in carbon emission reductions in all regions.

This suggests that in the near term, utilities and DER aggregators need to be aware of program designs for flexible loads that are based on profit maximization, as they may unintentionally lead to emission increases in some regions. Given that the Single Month, Year-Round, and Critical Hours programs for the Moderately Profit-Driven customer can realize 71%, 76%, and 72% of the revenue as the program for the Profit-Driven customer, across all scenarios and flexibility parameters, it may be desirable to offer such constrained programs to avoid negative climate impacts. Programs that are aimed at reducing carbon emissions can, for the most part, deliver positive grid service revenue everywhere, especially when the flexibility is provided by highly efficient building technologies. Across all regions, program types, scenarios, and flexibility parameters, over 75% of Climate-Driven customers can obtain positive revenue in the LowCarbon 2030 scenario.

5 Conclusions

After evaluating a marginal unit of technology-agonistic, shiftable, building flexible load under various program designs and grid scenarios, we conclude that a Year-Round program is likely to bring the greatest carbon reduction benefits for the Climate-Driven customer in the near term (2030), resulting in up to 488 kg CO_2e/kW of emission reduction. In the medium term (2040), the Profit-Driven customer is expected to generate significant revenue – up to $73/kW – from the Critical Hours program with a relatively low number of service hours required.

Even though profit-maximizing programs may inadvertently result in an increase in carbon emissions in some regions, a Year-Round program can still obtain 76% of the revenue benefit when shifting is restricted to only carbon-reducing hours. As the power system decarbonizes, it would be easier for Profit-Driven customers to simultaneously reduce carbon emissions while maximizing revenue. Thus, it is crucial for utilities, DER aggregators, and customers to consider local power system conditions when designing or adopting flexible load programs to avoid unintended consequences.

We showed the impacts of various building flexibility parameters on revenue and on carbon emissions. The time of service has a critical impact on revenue. Measures that can reduce dissipation rate, such as building envelop energy efficiency, would enhance both the revenue and emission reduction benefits. Moderate periods of building load flexibility (4 hours) can harness most of the revenue and emission reduction potential in the near term and medium term, and the incremental gain with longer duration of shifting is limited.

The benefits analyzed in the present study depend on the power system sending accurate price signals and emission signals; without these, the demand side resources would remain underutilized. FERC Order 2222 has opened doors for building flexibility to participate directly in wholesale power markets. Short of such direct participation, it is up to utilities to determine, and reflect back to customers, the time-varying value of their grid services. With the emergence of companies providing real-time grid emission data, it is important that utilities and DER aggregators design and implement flexible load programs in a way that considers estimated climate impacts along with grid cost reduction benefits.

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Appendix A. Social Cost of Carbon Assumptions

Table A-1. Social Cost of Carbon Assumptions

2020 U.S. dollar/ton CO_2

Year	IWG 2021	Ricke et al. 2018	Pindyck 2016	Bressler 2021	Cai, Lenton, and Lontzek 2016	EPA 2022
2030	89.481	417.506	275.406	258	226.609	144
2040	103.113	417.506	275.406	258	272.515	173

We use the mean of each study's estimates where available, and we convert all values to 2020 U.S. dollars. We assume a flat 2.5% discount rate to make these estimates comparable, even though Ricke et al. (2018) use an alternative time-varying discounting method.

Appendix B. Summary of Results

Grid service and emission results across all hours of usage, regions, building flexibility parameters for the four customer types and three potential building flexibility programs in LowCarbon 2040, MidCase 2030, and MidCase 2040 are summarized in Table B-1 through 6.

Table B-1. Range of Grid Service Revenue in LowCarbon 2040 [a]

Revenue ($/kW)	**Critical Hours**	**Single Month**	**Year-Round**
Profit-Driven	18 to 73	5 to 39	17 to 94
Moderately Profit-Driven	2 to 73	1 to 39	4 to 94
Moderately Climate-Driven	0 to 25	0 to 22	1 to 60
Climate-Driven	-179 to 24	-176 to 20	-520 to 57

[a] Negative revenue numbers indicate revenue loss. Positive revenue numbers indicate revenue gain.

Table B-2. Range of Carbon Emissions in LowCarbon 2040[b]

Emissions (kg CO2e/kW)	**Critical Hours**	**Single Month**	**Year-Round**
Profit-Driven	-18 to 93	-16 to 44	-137 to 91
Moderately Profit-Driven	-19 to -1	-16 to 0	-138 to -9
Moderately Climate-Driven	-26 to -7	-21 to -2	-184 to -5
Climate-Driven	-26 to -16	-21 to -7	-184 to -47

[b] Negative emission numbers indicate carbon emission reduction. Positive emission numbers indicate emission increase.

Table B-3. Range of Grid Service Revenue in MidCase 2030

Revenue ($/kW)	**Critical Hours**	**Single Month**	**Year-Round**
Profit-Driven	4 to 50	2 to 25	11 to 55
Moderately Profit-Driven	0 to 49	0 to 25	0 to 55
Moderately Climate-Driven	0 to 7	0 to 8	0 to 29
Climate-Driven	-13 to 6	-7 to 6	-38 to 20

Table B-4. Range of Carbon Emissions in MidCase 2030

Emissions (kg CO2e/kW)	**Critical Hours**	**Single Month**	**Year-Round**
Profit-Driven	-29 to 213	-31 to 101	-243 to 208
Moderately Profit-Driven	-32 to 0	-33 to 0	-259 to 0
Moderately Climate-Driven	-69 to 0	-59 to 0	-488 to 0
Climate-Driven	-69 to -13	-59 to -4	-488 to -29

Table B-5. Range of Grid Service Revenue in MidCase 2040

Revenue ($/kW)	**Critical Hours**	**Single Month**	**Year-Round**
Profit-Driven	5 to 65	2 to 29	8 to 68
Moderately Profit-Driven	0 to 65	0 to 29	0 to 68
Moderately Climate-Driven	0 to 13	0 to 15	0 to 34
Climate-Driven	-21 to 5	-22 to 8	-111 to 24

Table B-6. Range of Carbon Emissions in MidCase 2040

Emissions (kg CO2e/kW)	**Critical Hours**	**Single Month**	**Year-Round**
Profit-Driven	-23 to 332	-23 to 118	-215 to 506
Moderately Profit-Driven	-31 to 0	-23 to 0	-235 to 0
Moderately Climate-Driven	-57 to 0	-46 to 0	-460 to 0
Climate-Driven	-57 to -14	-46 to -4	-460 to -37