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Evaluating building decarbonization potential in U.S. cities under emissions based building performance standards and load flexibility requirements

Abigail Andrews, Rishee K. Jain *

Urban Informatics Lab, Department of Civil & Environmental Engineering, Stanford University, Office 269B, 473 Via Ortega, Stanford, CA, 94133, United States

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ABSTRACT

In an effort to decarbonize the built environment, municipalities across the United States are joining the National Building Performance Standard Coalition. The National Building Performance Standard Coalition is an effort by the United States federal government to encourage cities to design and implement effective and equitable building performance standards. A building performance standard is an energy policy that requires buildings to meet energy use or greenhouse gas emissions targets in effort to reduce the carbon intensity of buildings. In this paper, we examine the impact of implementing various building performance standards for commercial buildings in 15 cities and one county in the United States from 2024 to 2050. We first estimate the emission reductions associated from a null case (no building performance standard). Next, we implement two building performance standards: (1) an annual greenhouse gas emissions target and (2) a peak grid load flexibility requirement. Lastly, we combine the two to assess the potential impact of an integrated energy and demand building performance standard. We find that individually a load flexibility building performance standard does not contribute to significant emissions reductions but when paired with a greenhouse gas building performance standard it leads to a combined 89% reduction (a cumulative savings of 189 $MMtCO_2e$) across commercial buildings in the 15 cities and one county analyzed. This potential reduction represents a massive decarbonization scenario that far exceeds a 2050 80% decarbonization target and points to feasible policy pathways for meeting climate and sustainability goals.

1. Introduction

In the United States the building sector is responsible for 40% of greenhouse gas (GHG) emissions [1]. In response to the high carbon intensity of the built environment, municipalities across the United States are adopting Building Performance Standards (BPS) [2]. A BPS is an energy policy that aims to limit GHG-emissions of the built environment by mandating building to perform at or below a certain energy use intensity or GHG-emission limit. BPSs are akin to building benchmarking mandates (an energy policy package popularized in the United States in the 2010s) [3]. BPSs go further than benchmarking mandates as the latter ranks the energy efficiency of a building to its peers while the former prescribes a level of performance a building must achieve.

Benchmarking has proven to be a successful market mechanism towards decarbonization [4]. In 2009 New York City passed the *Greener Greater Building Plan*, a first-of-its-kind policy package [5]. The *Greener Greater Building Plan* includes Local Law (LL) 84, LL84

* Corresponding author. Office 269A, 473 Via Ortega, Stanford, CA, 94133, United States.
E-mail addresses: abigail.andrews@stanford.edu (A. Andrews), rishee.jain@stanford.edu (R.K. Jain).

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is a building benchmarking mandate for all buildings larger than 4,685 m^2 (50,000 ft^2) LL84 has since been amended with LL133 to also require buildings between 2,323 m^2 (25,000 ft^2) and 4,685 m^2 (50,000 ft^2) to annually benchmark their energy use [6]. LL84 has been an effective mechanism to lower energy use in New York City [4]. It is estimated that between 2011 and 2015 energy use in buildings covered by New York City's LL84 decreased by 14% and building owners avoided $267 million in energy costs [4,7,8].

Benchmarking mandates exist in over 40 cities and states in the United States [9]. Nearly all entities with a benchmarking mandate utilize Energy Star Portfolio Manager (ESPM) for data collection, processing, and Energy Star Score calculation. Several cities require the data from ESPM to be publicly disclosed. There are currently no benchmarking mandates that penalize or incentivize receiving a certain Energy Star Score [3]. BPSs extend benchmarking mandates by creating actionable GHG-emissions or energy targets in order to meet climate goals.

The first BPS was enacted in Washington D.C. in 2018 under Title III of the DC Law 22–257 [10]. CleanEnergy DC Omnibus Amendment Act of 2018 utilizes the EnergyStar Score as the performance metric starting in 2021 for buildings larger than 4,685 m^2 (50,000 ft^2). In 2019, New York City passed the ambitious urban sustainability policy package the *Climate Mobilization Act* [11]. This sweeping legislative package includes LL97, a BPS that places GHG-emissions limits on buildings larger than 2,323 m^2 (25,000 ft^2) [12]. Buildings that exceed GHG-emission limits will be subject to fines starting in 2024. The GHG-emission limits will become more conservative as New York City approaches the 2050 80% decarbonization target. Table 1 provides the landscape of existing BPSs [13].

The importance of BPSs for accelerating urban decarbonization was recognized by government officials and policy makers in the United States. In 2021, President Biden introduced the National Building Performance Standard Coalition in which city and state governments pledge to design inclusive and actionable BPSs by April 2024 [14]. As of December 2022, 38 states and cities have joined the National Building Performance Standard representing one-quarter of the United States building stock [15]. The majority of states and cities in the National Building Performance Standard are in the process of designing their BPS while 10 states and cities have enacted a BPS [13].

While municipalities across the United States continue to adopt BPSs, research that quantifies the impact of BPSs is limited largely to performance targets and technical guidelines [2,16,17]. Recent literature has explored the estimated GHG-emissions savings of BPSs and associated costs at an individual city level. One study found that with existing policies Seattle can reduce GHG-emissions 19% by 2050 and up to 34% by including buildings smaller than 1,858 m^2 (20,000 ft^2) [18]. The authors also discuss the impact of inaction, by delaying current policy implementation by just five years GHG-emissions savings would decrease to 12% [18]. A study of Washington DC's BPS found estimated GHG-emissions reductions of 30% in buildings covered under the 2018 BPS [3]. Other research considered the cost and feasibility of retrofits necessary to meet a BPS [16]. A study of Washington State found that multi-system retrofits are necessary for buildings to achieve targets set by BPSs [19]. We found only one study that assessed existing or potential BPSs in multiple cities [16]. The authors find that up to 85% of buildings covered by BPSs will be required to retrofit and many of these buildings will require a deep retrofit. The authors found that if buildings were prescribed to reach site EUI targets as set in ASHRAE-100 cities can reach up to 45% GHG-emission reduction with a 10-to-20-year payback period for necessary retrofits [2,16].

Beyond the United States, there is a growing body of research on the impact of BPSs. For example, researchers in China found in a null (business-as-usual) scenario the country will reach peak building emissions in 2040 (10 years after the target) but with periodic BPSs and market development building stock emissions (i.e., ultra-low energy buildings are enforced in 2025, net-zero energy buildings in 2030, zero energy buildings in 2035) can decrease 50% by 2060 [20]. In Europe, researchers have largely examined pairing BPSs with retrofit and renovations as the European Union's Energy Performance of Buildings Directive requires energy retrofits in the worst performing buildings (as defined by Energy Performance Certificate labeling). One study that parametrically evaluated renovation scenarios found that the building stock in Umbria, Italy can achieve up to 28% reduction by 2030 with directive compliance [21]. In a case-study of Estonian office buildings researchers found that office buildings can reduce CO_2e emissions up to 52% by 2050 when renovations compliance is met [22]. In Finland, researchers used multi-objective optimization to find that apartment buildings built prior to 2002 may reduce emissions up to 82% by 2050 by performing the most cost-effective renovations and exceed the European Union's decarbonization target [23].

A comparative policy analysis of Minimum Energy Performance Standards across Scotland, England and Wales, the Netherlands, and France found that standards should be based on actual consumption rather than Key Performance Indicators (KPI), namely the Energy Performance Certificate [20]. In the United States, of the seven BPSs enacted only Washington D.C. utilizes a KPI (Energy Star Score) [13]. Overall, research finds the harmonization of policy at the national level is essential for success in BPSs [20–22], this finding is encouraging for the National BPS coalition.

Table 1
Existing BPSs enacted on the city or county level. There is diversity in performance metric and penalization structure to achieve decarbonization goals.

CITY	Year enacted	Performance metric	Penalization structure
BOSTON, MA	2021	Annual GHG-emissions	$234/$MtCO_2e$
CHULA VISTA, CA	2021	Energy star score, Weather normalized site EUI	$750-$2500 non-compliance
DENVER, CO	2021	Weather normalized site EUI	$0.21/kWh
MONTGOMERY COUNTY, MD	2022	Site EUI	TBD
NEW YORK CITY, NY	2019	Annual GHG-emissions	$268/$MtCO_2e$
ST. LOUIS, MO	2020	Site EUI	$1-$500 non-compliance/day
WASHINGTON, DC	2018	Energy star score	$108/$m^2$ (10/ft^2)

This paper aims to extend previous work to evaluate the impact of a GHG-emissions BPS across multiple United States cities. The existing, albeit limited, literature largely focuses on energy BPSs. A GHG-emissions based BPS provides unique insights into building performance and can be advantageous for buildings that do not burn fossil fuels in light of widespread building electrification [23,24].

BPSs, like the benchmarking mandates that predated them, emphasize energy reduction [2,25]. An emerging body of research suggests that buildings must implement energy reduction strategies in addition to load flexibility measures [26–28]. In the United States, the concept of merging energy efficiency and load flexibility is commonly referred to as Grid Interactive Efficient Buildings, or GEBs. Retrofitting buildings nationwide to become Grid Interactive Efficient Buildings would lead to GHG-emissions reductions up to 80 million metric tons of carbon dioxide equivalent ($MMtCO_2e$), or the equivalent to 6% of all power sector GHG-emissions [29,30].

At the time of writing there are no building energy policies that explicitly promote Grid Interactive Efficient Buildings or load flexibility in the United States. There exists a variety of programs at the utility level that span the spectrum of coordination between load flexibility (e.g., demand response, demand flexibility) and energy efficiency (e.g., energy efficiency measures, energy management) [31,32]. Load flexibility and grid interactivity can be incorporated in a BPS as a mechanism to encourage Grid Interactive Efficient Buildings [31,33].

In this paper, we evaluate the potential GHG-emissions reductions from various novel BPS policies across large United States cities in commercial buildings. We consider a national GHG BPS, a national load flexibility BPS, and an integrated BPS and also determine how the building stock would have decarbonized without a new policy intervention. Our work extends the concept of a BPS from a stand-alone energy policy to a policy that promotes load flexibility and energy efficiency. This integration is necessary to incentivize Grid Interactive Efficient Buildings.

2. Methods

Our methodology aims estimate GHG-emissions reductions attributed to the enactment of a BPS in various United States cities. We consider two BPSs, a GHG-emissions standard (akin to New York City's LL97) and a novel load flexibility standard.

2.1. Policy scenarios

In order to understand the relationship between policy specifications and the resulting GHG-emissions reductions over time we consider three policy scenarios with variation in addition to a null model. The model starts in 2024 and continues annually until 2050 for commercial buildings. When utilizing public building energy data (Scenario 1) we utilize a broad definition of commercial buildings to account for the diversity of building use-types and the existence of mixed-use commercial buildings in real world data (Table 2).

Each building's emissions are calculated by applying the reductions from the null model in addition to any reductions in energy use or demand from each policy scenario. It is assumed that each policy scenario is successfully implemented (i.e., buildings will meet their GHG-emissions targets) unless stated otherwise.

2.2. Policy scenario 0: null model/business as usual scenario

The null model, Scenario 0, represents the expected GHG-emissions reductions from 2024 to 2050 without a national BPS intervention. Changes in building technologies and the electric grid's portfolio will impact the building stock's GHG-emissions with or without intervention. We adopt the U.S. Energy Information Administration's (EIA) Annual Energy Outlook 2023 Energy-Related Carbon Dioxide Emissions by Sector and Source for the commercial sector in addition to the Key Indicators and Consumption data for the commercial sector 2024-2050 [34]. We subset the existing total floor area to the floor area in our dataset and scale the estimated GHG-emissions accordingly. We do not modify the reference case data further.

2.3. Policy scenario 1: greenhouse gas emissions standard

In Scenario 1, we consider a BPS that calls for the absolute reduction of GHG-emissions with decreasing quinquennial GHG-emissions intensity limits. GHG-emissions must be reduced to the intensity limit specific to each building type and city.

New York City's LL97 provides a robust set of guidelines for GHG-emissions intensity limits. We therefore model our GHG-emissions intensity limits off New York City's LL97 as the city has set GHG-emissions intensity limits through 2050, unlike most of the other municipalities with a BPS where emission limits are set through 2030. In order to recognize the difference between GHG-emissions factors from regional grids we modify the LL97 GHG-emissions limits for each city as follows. First, we compute the percent of buildings in New York City that will meet the 2025 GHG-emissions limit based on their 2019 GHG-emissions. That percent becomes the cut off for each other city. For example, in 2019 60% of hotels in New York City performed at or below the 2025 GHG-emissions limit. Therefore, the 2025 GHG-emissions limit for hotels for Los Angeles is set as the 60th percentile of GHG-emissions for that set of

Table 2
Overview of scenarios in policy model.

SCENARIO #	Performance Metric	Covered Buildings
0	–	Commercial: business
1	GHG-emissions, decreasing targets every 5-years	Commercial: business, educational, mercantile
2	DF-requirement, increasing event days every 5-years	Commercial: business
3	GHG and DF	Commercial: business

buildings. We then use the percent decrease in the quinquennial GHG-emissions limits provided by New York City's LL97 to set GHG-emissions intensity limits through 2050 for each city and building type.

Buildings are expected to reach their quinquennial GHG-emissions limits by the target year. We compute the emissions for years succeeding the baseline year by multiplying the emissions limit ($MtCO_2e/m^2$) by the buildings floor area. The decrease in GHG-emissions year-to-year is randomly selected from the uniform distribution between the start year, n, GHG-emissions s and the target year, n + 5, GHG-emissions.

2.4. Policy scenario 2: load flexibility standard

In Scenario 2, we consider a BPS that calls for energy demand reduction during peak grid events. Buildings may either shed electric load during peak hours or shift electric load from peak hours to non-peak hours during an event. The number of events and the percent load reduction is increased quinquennially. We define an event as the n highest electric demand days for the regional grid between 12:00 – 9:00 p.m. We use 2019 electric grid data in order to best match our annual energy use data. Buildings can shed between 0% and 27.5% of their electric load. This range was identified from a literature review on demand flexibility that found smart buildings are able to reduce peak load by 25.5% and shift peak load by 25% [36–39].

Building Benchmarking Mandates provide annual energy use data that cannot be used to model demand flexibility. Therefore, we utilize simulation data to exploit time-series energy data as done in previous work with 2018 ComStock data [40]. ComStock is a highly granular building energy model that aims to accurately represent the United States building stock. The ComStock dataset is generated with a probability distribution of key building characteristics from a wide array of data sources to build approximately 350,000 building energy simulations. These energy simulations then estimate energy consumption across the six million commercial buildings in the United States [40]. ComStock does not represent individual buildings characteristics but rather the diverse building characteristics found across the United States building stock. We use county-level ComStock data to simulate 1-h interval energy use data large office buildings in each of the 15 cities and one county. We only simulate buildings that are above each municipalities benchmarking ordinance's commercial minimum floor area. This provides us with a fuel-type load profile for each municipality. We then construct hourly electric load profiles for each office building in the cities dataset by linearly scaling the annual electricity use of an individual building to the hourly electricity use of the simulated ComStock building. This provides us synthetic electric load shape data (Fig. 1).

Next, we use 2019 regional electric grid data from the EIA and extract the hourly carbon intensity of electricity data for each of the eight grid regions the 15 cities and one county lie in. The hourly emissions profile is constructed by simply multiply electricity use (kWh) by the associated emissions factor ($MtCO_2e/kWh$). On each peak-day event, we use the synthetic emissions profile to model the impact of demand-reduction through load shedding or load shifting by the percent prescribed in each policy scenario. Electric load is shed or shifted over a randomly selected 4-h window during peak hours (Table 3). If a building shifts electric load the electric load is reduced over the 4-h window and added to a randomly selected 4-h window during non-peak hours. Emissions are calculated for each target year as such. Buildings are expected to reach their quinquennial demand reduction or demand shedding goal by the target year. The target includes an increase in number of events in addition to an increase in the amount of electric load shed or shifted. Buildings can meet the target from either shedding or shifting (randomly selected) between the start year, n, and the target year, n + 5.

2.5. Policy scenario 3: integrated standard

The final scenario consists of both GHG-emissions and load flexibility targets. Buildings must reach both. GHG-emission reductions associated with increased flexibility may be considered to the contribution of the GHG-emissions reduction target. We use the GHG-emissions limits from Scenario 1 and set GHG-emissions reductions of 12.5% in 2025, 2030, 2035 and 22.5% in 2040, 2045, 2050 with increasing number of peak days.

3. Data

This paper utilizes publicly disclosed data from benchmarking mandates in 15 different cities and one county in the United States. The cities include Boston, Cambridge, Chicago, Denver, Evanston, Kansas City, Los Angeles, Minneapolis, Montgomery County, New York City, Orlando, Philadelphia, Portland, Reno, Seattle, and Washington DC. The data is from calendar year 2019. Some cities with publicly disclosed Building Benchmarking Mandates were excluded from this paper if data was not disclosed in 2019 or if GHG-emissions data was not included in the disclosure (for example, San Francisco only publishes total annual energy use data). Unlike other open-data benchmarking and BPS studies we do not include tax assessor data [18,42]. While tax assessor data provides useful additional information for building benchmarking models, we did not find it necessary for our BPS model. The number of buildings range from merely 23 in Reno, NV to 26,024 in New York, NY.

We observed diversity across what data each city discloses and the unit of measurement for each data feature. Therefore, we recode and convert unit of measurement as necessary for consistency across data features. We then cleaned the data by removing any observation that did not comply to the local benchmarking ordinance or that was not required to comply, this includes buildings that voluntarily complied (such as exempt properties or buildings with floor area smaller than mandated). We additionally remove any observation where the site energy use intensity, floor area, property type, or GHG-emissions are missing. We also remove any duplicate properties. We remove any observation where Site EUI is above 3,155 kWh/m^2 (1,000 $kBtu/ft^2$) [43]. We do not apply any additional data cleaning. Table 4 includes the number of buildings by property type, the total GHG-emissions of benchmarked buildings, and the relevant benchmarking ordinance for the 15 cities and one county.

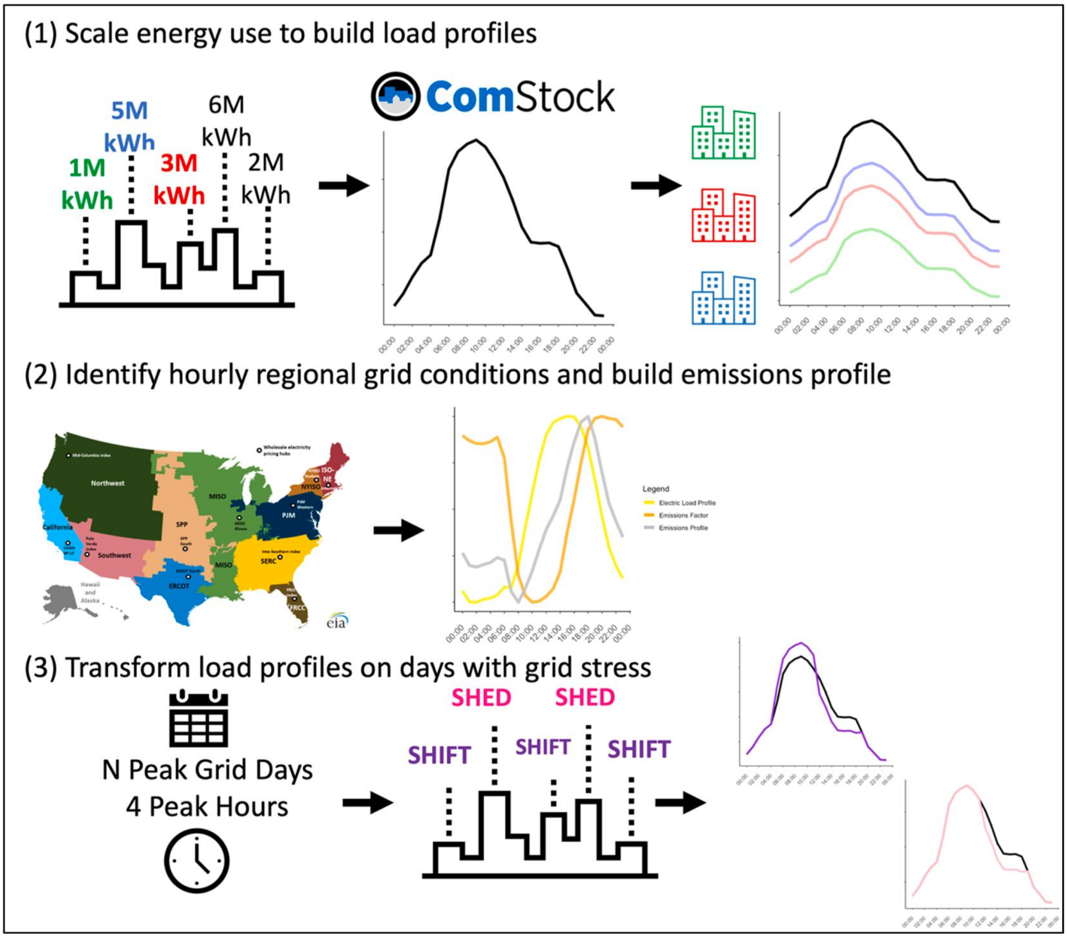

Fig. 1. Method for computing load flexibility profiles. Simulated hourly data from ComStock is linearly to match annual energy use from benchmarking data then paired with grid data to model shedding and shifting dynamics. U.S. sub-grid regions map from EIA [35].

Table 3
Peak Hours for each city and associated grid region. Peak hours vary municipality to municipality due to the variation in fuel mix from the electric provider. The fuel mix of individual electric providers is not required to be disclosed in all states nor are renewable portfolio standards [41].

CITY	Peak Hours	Grid Region
BOSTON, MA	9:00 a.m. – 6:00 p.m. (summer) 8:00 a.m. – 9:00 p.m. (winter)	Northeast
CAMBRIDGE, MA	9:00 a.m. – 6:00 p.m. (summer) 8:00 a.m. – 9:00 p.m. (winter)	Northeast
CHICAGO, IL	2:00 p.m. – 7:00 p.m.	Mid-Atlantic
DENVER, CO	3:00 p.m. – 7:00 p.m.	Northwest
EVANSTON, IL	2:00 p.m. – 7:00 p.m.	Mid-Atlantic
KANSAS CITY, MO	4:00 p.m. – 8:00 p.m.	Central
LOS ANGELES, CA	4:00 p.m. – 9:00 p.m.	California
MINNEAPOLIS, MN	2:00 p.m. – 7:00 p.m.	Mid-West
MONTGOMERY COUNTY, MD	7:00 a.m. – 11:00 a.m. & 5:00 p.m. – 9:00 p.m.	Mid-Atlantic
NEW YORK, NY	2:00 p.m. – 6:00 p.m.	New York
ORLANDO, FL	11:00 a.m. – 1:00 p.m. & 6:00 p.m. – 8:00 p.m.	Florida
PHILADELPHIA, PA	2:00 p.m. – 6:00 p.m.	Mid-Atlantic
PORTLAND, OR	3:00 p.m. – 8:00 p.m. (summer) 6:00 a.m. – 10:00 a.m. & 5:00 p.m. – 8:00 p.m. (winter)	Northwest
RENO, NV	1:00 p.m. – 6:00 p.m. (summer) 5:00 p.m. – 9:00 p.m. (winter)	Northwest
SEATTLE, WA	6:00 a.m. – 10:00 p.m.	Northwest
WASHINGTON DC	12:00 p.m. – 8:00 p.m.	Mid-Atlantic

Table 4
Data overview of the cities and one county analyzed in this study. The available data has significant range in dataset size.

CITY	Number of Properties	CO_2e (1000 Metric Tonnes)	Benchmarking Ordinance
BOSTON, MA	422	571	C, R ≥ 3,252 m² (35,000 ft²) All P
CAMBRIDGE, MA	10	43	C ≥ 32,516 m² (350,000 ft²) All P
CHICAGO, IL	361	1,128	C, R, P ≥ 4,645 m² (50,000 ft²)
DENVER, CO	723	872	C, R, P ≥ 2,323 m² (25,000 ft²)
EVANSTON, IL	84	108	C, R ≥ 1,858 m² (20,000 ft²)
P ≥ 929 m² (10,000 ft²)			
KANSAS CITY, MO	119	348	C, R ≥ 9,290 m² (100,000 ft²) P ≥ 929 m² (10,000 ft²)
LOS ANGELES, CA	923	467	C, R ≥ 1,858 m² (20,000 ft²) P ≥ 697 m² (7500 ft²)
MINNEAPOLIS, MN	159	372	C, R ≥ 4,645 m² (50,000 ft²) P ≥ 2,323 m² (25,000 ft²)
MONTGOMERY COUNTY, MD	462	480	C ≥ ≥ 4,645 m² (50,000 ft²) All P
NEW YORK, NY	4,880	6,083	C, R ≥ 2,323 m² (25,000 ft²) P ≥ 929 m² (10,000 ft²)
ORLANDO, FL	110	130	C, R ≥ 4,645 m² (50,000 ft²) P ≥ 929 m² (10,000 ft²)
PHILADELPHIA, PA	624	1,238	C, R ≥ 4,645 m² (50,000 ft²)
PORTLAND, OR	432	246	C ≥ 1,858 m² (20,000 ft²) R ≥ 50 units P ≥ 465 m² (5000 ft²)
RENO, NV	4	5	C ≥ 9,290 m² (100,000 ft²)
SEATTLE, WA	799	112	C ≥ 1,858 m² (20,000 ft²)
WASHINGTON DC	708	972	C, R ≥ 4,645 m² (50,000 ft²)

4. Results and discussion

4.1. Scenario 0

We model the expected trajectory of building-level GHG-emissions for each of the 15 cities and 1 county if there was no policy intervention. It is expected that the electric grid will become less carbon intensive and building technology become more efficient, therefore a natural decline in GHG-emissions is consistent with previous work [44]. The null scenario is location agnostic, and we observe a 28% reduction in commercial building GHG-emissions over the 30-year period of 2019-2049. Across the selected municipalities buildings reduce GHG-emissions 2.89 $MMtCO_2e$ by 2050 (baseline year 2019). Therefore, we can attribute nearly a third of building-level GHG-emissions reductions to a cleaner electric grid and more efficient building technologies. The null model did not include any assumptions on load growth due to electrification nor considered the new construction and/or demolishing of existing buildings.

4.2. Scenario 1

We determine that a GHG-emission BPS (akin to New York City's LL97) provides substantial GHG-emissions reductions through 2050 with emissions in 2050 11.1 $MMtCO_2e$ lower than 2019 (and a cumulative emissions reduction of 177 $MMtCO_2e$ across over 10,000 buildings). Fig. 2 provides the quinquennial GHG-emissions reductions for the median building GHG-emissions for each municipality by property type. In some cities we observe a sharp change in slope starting in 2030 due to stricter GHG-emissions targets enforced for that target period. GHG-emissions limits were set with two criteria (1) for 2025-2030 target was based on the percentile of the corresponding building type from New York City's LL97 GHG-emissions limits for 2025-2030 and (2) for 2030 onwards the 2025-2030 target was reduced by the percent difference of the next target LL97 target. Therefore, if many buildings GHG-emissions are already below the emissions limit for a target year, such as is the case for Boston, Chicago, Evanston, Kansas City, Minneapolis, Montgomery, Philadelphia, Reno, and Washington D.C. from 2025 to 2030, the curve is flat. If many buildings are near the target the reduction would continue to be constant, such as New York City and Seattle. If instead the majority of buildings were not close to the next target year a sharp decline is necessary to meet the next target, as such is the case in Cambridge, Chicago, Minneapolis, Montgomery, Philadelphia, Reno, and Washington D.C. 2030-2035. Cities with a small and non-sharp slope (Seattle) have more efficient existing building stocks.

We find that all cities exceed 80% decarbonization under the GHG-based BPS in commercial buildings (office, mercantile, educational) (Table 5). Overall, Cambridge has the lowest total decarbonization (88% reduction) while Seattle is the highest at a 93% reduction. Previous work [18] has found that Seattle would realize considerably less emission reductions of 34% by 2050 under an EUI BPS policy. We postulate that this delta is due to this previous work assuming a less stringent BPS policy that only requires buildings to reach the median EUI for the building use type every five years [18]. We utilize the more ambitious New York City's LL97 as the basis of our BPS policy as it is one of the few BPS policies that has been codified by law and represents a potential pathway for other cities to follow. However, we also acknowledge that Seattle has a relatively low emissions factor for electricity due the dominance of hydropower (as seen in Fig. 2) and therefore may not strive for as deep decarbonization goals as other cities [18]. Additionally, cities

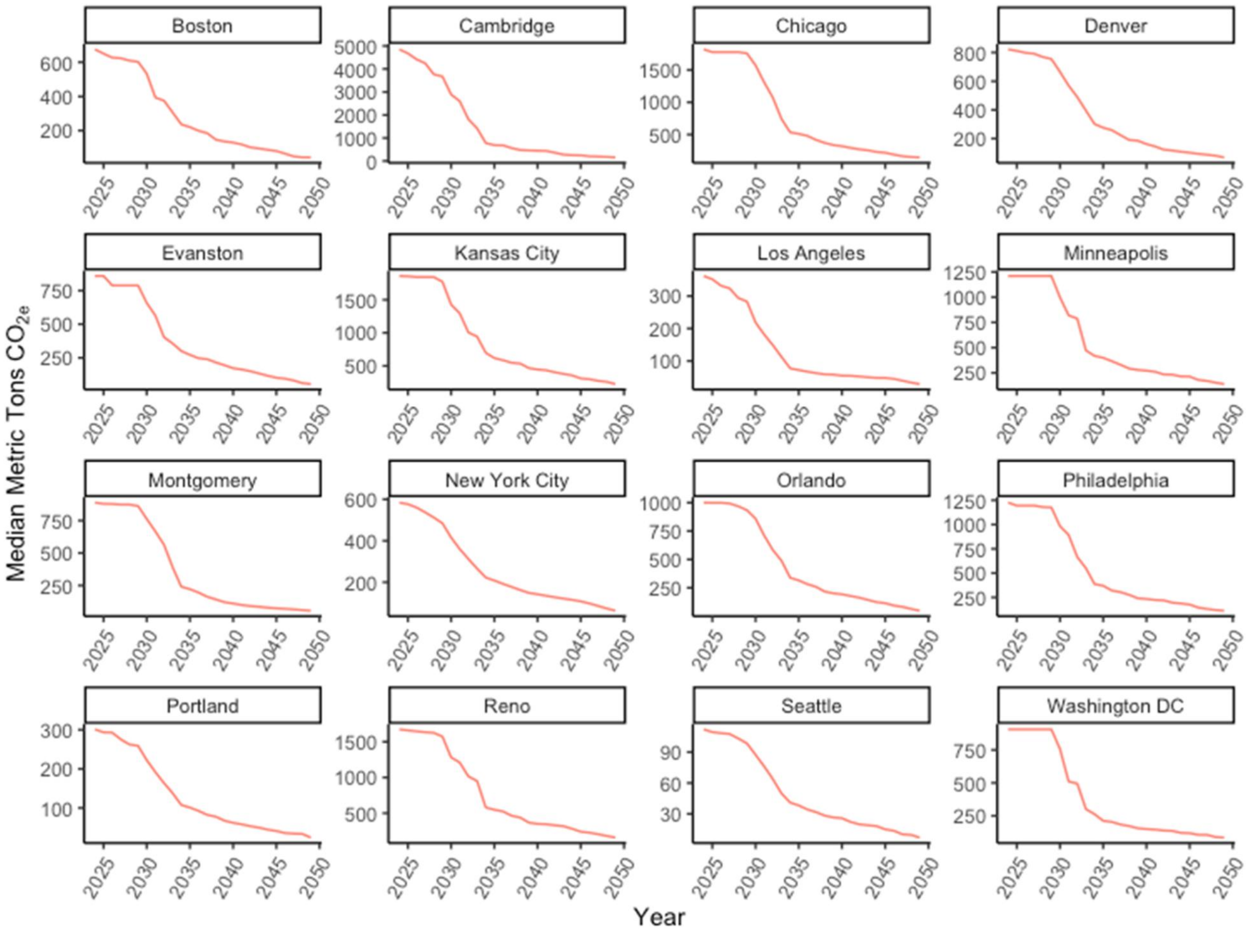

Fig. 2. Median building-level GHG-emissions of covered buildings for a GHG BPS (Scenario 1).

Table 5
Absolute GHG-emissions reduction of covered buildings for a GHG-BPS (Scenario 1).

CITY	
BOSTON, MA	91.5%
CAMBRIDGE, MA	88.0%
CHICAGO, IL	91.3%
DENVER, CO	90.2%
EVANSTON, IL	941.4%
KANSAS CITY, MO	88.6%
LOS ANGELES, CA	89.7%
MINNEAPOLIS, MN	89.5%
MONTGOMERY COUNTY, MD	92.7%
NEW YORK, NY	91.4%
ORLANDO, FL	91.3%
PHILADELPHIA, PA	88.5%
PORTLAND, OR	90.5%
RENO, NV	90.1%
SEATTLE, WA	93.1%
WASHINGTON DC	91.8%

that have enacted their own BPS have not set emissions limits as far out as New York City and therefore New York City's LL97 gives us longitudinal guidance. Previous work [16] has also characterized BPS as a "high effort, high reward policy tool" and highlights the financial and implementation barriers for such programs. Because our work does not consider the financial and implantation feasibility of the proposed BPS, it can be interpreted to be an upper bound of potential emissions reductions. However, we note that our modeled BPS has been codified in law by New York City (largest city in the U.S.) and thus represents a realistic potential pathway for both New York and other municipalities around the United States.

4.3. Scenario 2

A load flexibility BPS provides modest GHG-emission reductions in commercial buildings. This a result of buildings shedding or shifting electric load over only 4 h on specific event days. We provide the results of increasing number of event days and increasing percent reduction for Philadelphia in Table 6. We observe that shedding electric load provides substantially more GHG-emission reductions then shifting or a combination of shifting and shedding. This may be in part due to the randomization of shifting hours instead of a targeted approach to shift to hours when the electric grid is cleaner. We find that increasing the number of event days provides greater emission reductions than increasing the percent of electric load shed. Overall, the GHG-emissions reductions from this BPS are low. If Philadelphia adopted a BPS of 12.5% load reduction with increasing number of event days with half buildings shifting and half buildings shedding load by 2050 the mandate would only reduce an additional 0.12% of GHG-emissions compared to Scenario 0. Across all peak event hours Philadelphia witnesses a mean emissions reduction of 7.14% through mandated 12.5% load flexibility. Our results align well with the limited existing work on load flexibility that finds GEBs can provide 6% emissions reduction by 2040 and industrial buildings can reduce emissions up to 5% through active load shedding and shifting of electric load [45,46]. The savings from demand flexibility are smaller than that of efficiency alone; however, this is not to dismiss the importance of shifting electric load, the goal of load shifting is to use electricity when the grid is either less stressed or less carbon intensive [47]. If peak demand is lowered through shifting or shedding load this may result in less fossil intensive electricity added to grid and can in turn further accelerate emissions reductions [48,49]. While our emissions savings are minimal, under more aggressive intermittent renewable energy penetration and grid instability assumptions load flexibility may yield 18% carbon savings in the near-term and large emissions reductions on the order of 43-51% in commercial buildings by 2050 [29,50].

4.4. Scenario 3

GHG-emission reductions are driven by GHG-emissions targets with enhancements from load flexibility requirements (Table 7, Fig. 3). The maximum difference between Scenario 0 and Scenario 2 is 0.33% load reduction while 88.34% for Scenario 1. These results are indicative that while load flexibility alone cannot be a robust building performance, standard additional reduction provided by load flexibility can help in edge cases. We expect the load reduction associated with flexibility to increase as intermittent renewables penetration exists and thus such load flexibility could provide further synergistic reductions in the future [51]. We do not believe that energy efficiency measures from Scenario 1 are cannibalizing load flexibility potential from Scenario 2 due to previous work quantifying this relationship [52,53]. Scenario 3 provides a cumulative 189 $MMtCO_2e$ of GHG-emissions reduction between 2024 and 2050. As discussed in Scenario 1, our results exceed emissions reductions found in other BPS research that may be in part due to a lack of thermodynamic bounds and multi-city standards [3,16,18]. For these results to be realized deep retrofits will be necessary to allow occupant comfort while operating an extremely energy efficient building [16,54,55].

5. Limitations and future work

Our analysis estimates the potential GHG-emission reductions of BPSs. We highlight the integral role BPSs will play in climate and decarbonization policies for cities across the United States. However, this conclusion is not without limitations. We assume that every building covered by a BPS can without significant burden meet its GHG-emissions reduction goals by each target year. In reality this would require deep retrofits of many buildings that may be cost prohibitive or currently technologically infeasible [16]. Cities can re-

Table 6
GHG-emissions reduced from a flexible load-based BPS in Philadelphia, PA. The BPS mandates buildings reduce electric load by 12.5% on increasing event days per year or increase load flexibility per year over 25 event days.

	Event Days	All buildings shift 12.5% ($MtCO_2e$ reduction)	All buildings shed 12.5% ($MtCO_2e$ reduction)	Split shed-shift 12.5% ($MtCO_2e$ reduction)	Required Load Flexibility	Split shed-shift 25 event days ($MtCO_2e$ reduction)
2020	0	0.0	0.0	0.0	0%	0.0
2025	15	182.3	702.8	493.7	2.5%	459.6
2030	20	275.6	962.2	688.0	7.5%	609.9
2035	25	350.6	1,202.5	863.0	12.5%	739.9
2040	30	414.7	1,426.8	1,023.6	17.5%	856.2
2045	35	498.1	1,675.7	1,206.7	22.5%	1,076.3
2050	40	696.2	2,199.4	1,602.1	27.5%	1,553.6

Table 7
Comparison of GHG-emission reduced between the null scenario and Scenario 1 – 3.

	Scenario 1 Reduction from Scenario 0	Scenario 2 Reduction from Scenario 0	Scenario 3 Reduction from Scenario 0
2025	1.73%	0.08%	1.81%
2030	15.15%	0.12%	15.27%
2035	60.19%	0.16%	60.35%
2040	73.44%	0.20%	73.64%
2045	81.34%	0.25%	81.59%
2050	88.34%	0.33%	88.66%

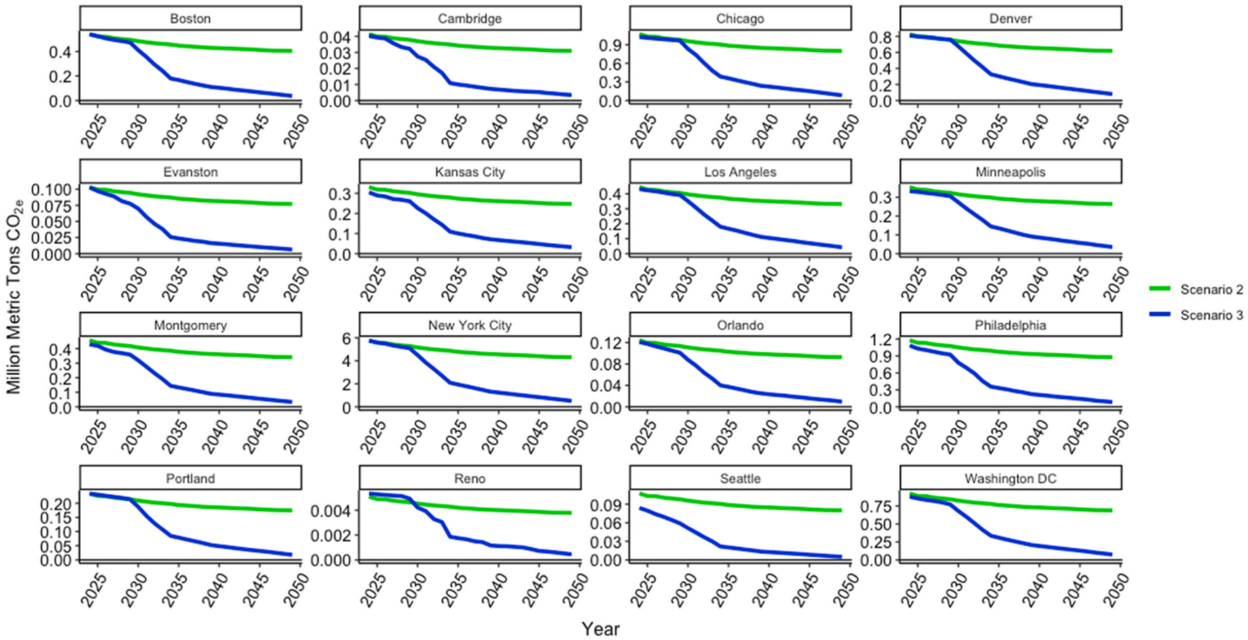

Fig. 3. Scenario 2 and 3 reduction by city.

duce the financial burden of GHG-emissions reductions through low-interest loans for retrofits. For example, in New York City Property Assessed Clean Energy (PACE) provides fixed-rate loans for energy efficiency upgrades and is a tool for buildings to meet LL97 targets [56]. PACE financing is not unique for New York City and complementary programs exist at the state-level across the country [57].

Our model assumes a linear reduction GHG-emissions or increase in load shedding and shifting. We model the future building stock based on existing buildings in 2019 and do not account for changes to the building stock via new construction and/or demolition of existing buildings. Future work should consider utilizing projected hourly GHG-emissions factors if data is available in addition to modeling the building stock as non-static. However, this work still provides a first-of-its-kind comprehensive assessment of the potential for BPS policies and potential synergistic effects of peak load grid flexibility requirements.

Additionally, our work aims to perform our analysis at scale and thus does not consider individual nuances to each city in respect to building stock and policy challenges. We utilize individual data for each city but base our GHG-emissions reduction goals off of New York City's LL97, which maybe more ambitious than other municipalities. However, our approach provides an upper bound estimate of potential emissions reductions given the aggressive emission reduction goals adopted from New York City.

6. Conclusion and implications

In response to the growing legislative support for the enactment of BPSs, this paper evaluates the emissions reductions that may be associated with best-case-scenario BPSs for commercial buildings in 15 cities and one county across the United States from 2024 to 2050. Our paper models emissions reductions without a building performance standard (null scenario), an annual greenhouse gas emissions target (Scenario 1), a novel peak grid load flexibility requirement (Scenario 2), and an integrated energy and demand building performance standard (Scenario 3). We utilize a mixture of real urban energy data from benchmarking disclosure ordinances (Scenario 1 and 3) and urban stock model data (Scenario 2). Our results find that if cities adopt ambitious BPSs emission reduction policies they can exceed 2050 decarbonization targets. We find that an integrated emissions and demand flexibility policy (Scenario 3) can save a cumulative 189 $MMtCO_2e$ across 10,000 large commercial buildings.

Our research described above provides an analysis of what GHG-emissions reductions may occur from widespread BPSs. We extend on existing literature from analyzing a load flexibility BPS to address the need for load flexibility in addition to energy efficiency. This work provides a projection of GHG-emissions reductions under ideal conditions and therefore cannot improve BPSs alone. However, the information gained from this analysis can be considered in designing BPSs and facilitating widespread adoption by cities across the United States and globally. A potential barrier to implementing a BPS as described in Scenario 3 (and Scenario 2) is a lack of robust research and modeling mechanisms on the potential of demand-flexibility as a grid-resource. Policy makers must allocate funding for research and development of load flexible BPSs as they are likely to provide synergistic benefits and may provide alternative pathways for building decarbonization. Although the additional GHG-emissions reductions are minimal compared to the GHG-emission reductions found in Scenario 1, the need for flexible electric loads will increase in importance over the next three decades as intermittent renewable penetration grows.

Overall, this work contributes to the growing body of literature at the intersection of building decarbonization and sustainable energy policy. BPSs can complement a wide variety of building energy policies such as electrification mandates, next-generation energy codes, and retrocommissioning. These complementary mandates can drive energy reduction and decarbonization allowing buildings to reach BPSs with more ease. For example, electrification mandates may contribute to a reduction in GHG-emissions as electricity has a lower emissions factor than natural gas [18]. Additionally, energy codes and retrocomissioning mandates target inefficiencies in buildings to minimize wasted energy. Reaching our aggressive climate goals of reducing 80% of our emissions by 2050 will likely require widespread adoption of BPS and load flexibility policies as well as require innovations at the building science and energy policy interface.

Credit author statement

Abigail Andrews: Conceptualization, Methodology, Software, Writing – Original draft preparation, Writing – Review and editing, Rishee K. Jain: Conceptualization, Writing – Review and editing, Supervision.

Declaration of competing interest

Our declaration of interest is none.

Data availability

Data will be made available on request.

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