Long-term carbon intensity reduction potential of K-12 school buildings in the United States

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Abstract

School buildings have a great potential for carbon emission reduction since their annual emission is about 72 million metric tons. Currently, more than 30% of school buildings were built before 1960 and are underperforming. To effectively reduce carbon emissions via school building retrofits, it is critical for policymakers to understand the carbon intensity reduction potential of retrofitting school buildings in different regions. Hence, this study develops a method to comprehensively assess the long-term carbon intensity reduction potential of aggregated commercial buildings on a county-by-county basis in the continental U.S. We apply this method to the K-12 school buildings including primary and secondary school buildings. This paper predicts the carbon intensity reduction potential of K-12 school buildings with eight building retrofit measures from 2022 to 2050 in the continental U.S. The results reveal several interesting findings: (1) In the approximately 3,000 counties of the U.S. from 2022 to 2050, the carbon intensity reduction potential of retrofitting K-12 school buildings in each county ranges from 0.41 kg/m^2 to 40.00 kg/m^2. (2) Even in the same climate zone, the trends of carbon intensity reduction potential from 2022 to 2050 are different depending on their electricity sources. For example, in a hot and humid climate zone, the carbon intensity reduction potential in Florida will decrease from 2044 to 2048. However, in Mississippi, the carbon intensity reduction potential from 2044 to 2046 will increase due to the termination of the nuclear energy usage. (3) Generally, reducing lighting power density leads to more carbon intensity reduction in most states, but it might not be applicable for states with high clean energy penetration, such as Washington.

Keywords: K-12 school building; Carbon intensity reduction; Building energy simulation; Large-scale simulation.

1 Introduction

To mitigate climate change caused by greenhouse gas (GHG), the United States (U.S.) has outlined a pathway to reduce carbon emissions 50% by 2030 [1] and 80% by 2050 [2]. Being one of the significant infrastructures in the U.S., K-12 school buildings, including primary and secondary schools, have a great potential to reduce carbon emissions. According to the climate advocacy organization Generation180, school facilities annually emit about 72 million metric tons of carbon dioxide, which is equivalent to the emissions from about 8.6 million homes [3]. Currently, more than 30% of school buildings are constructed before 1960 and are underperforming [4,5].

The underperforming buildings are buildings with low energy efficiency and high carbon emission intensity. Carbon intensity, which is the kilograms of carbon dioxide equivalent emitted per square meter, is one of the emerging metrics to measure the carbon emissions of buildings [6–8]. Hence, it is critical for the policymaker to know the reduction potential of carbon intensity for underperformed buildings by adopting building retrofit measures. The high operating cost of the K-12 school buildings also forces public administrations to make strategic decisions concerning the refurbishment of the school building stock. According to the 2012 Commercial Buildings Energy Consumption Survey (CBECS) conducted by the U.S. Energy Information Administration (EIA), schools annually spend around $8 billion on utility bills [9]. Moreover, reducing the carbon intensity of K-12 school buildings is a good practice for promoting sustainable development for the pupils and their families [10].

The existing study has proved the effectiveness of building retrofits to reduce carbon intensity in specific cities [11,12]. There are several building retrofit measures that have the potential to reduce carbon intensity, such as increasing the insulation of the building envelope, improving the efficiency of the HVAC system, and adjusting the lighting power density of buildings [13–21]. Moreover, building retrofits have a positive economic impact on reducing the operational costs of buildings, which can be an incentive for stakeholders to adopt the building retrofit measures, reducing carbon intensity as a result [22]. Gamarra et al. indicated that schools could reduce the fossil energy demand of the building in the operation and maintenance phase via building retrofits in a hot climate zone [23]. Many researchers realize that carbon intensity reduction on the county level is very important to achieve low-carbon development goals [24–27].

However, challenges remain regarding presenting comprehensive carbon intensity inventories at the county level. For the U.S., the situation becomes particularly difficult because of the significant geographical and social-economic diversity across the country. Furthermore, generating comprehensive carbon intensity inventories requires very detailed carbon accounting for each county as well as a comprehensive understanding of the local climate. Compared with states, counties have various definitions regarding their boundaries and non-centralized statistics, which produce uncertainties in carbon intensity calculation. Facing this challenge, a method emphasized on a county-by-county basis is needed to predict the carbon intensity reduction potential of school buildings. Carbon assessment on a county-by-county basis is a key research direction in the field of carbon neutrality. Understanding carbon intensity at the county and regional levels have been highlighted in the carbon management literature [28–30].

The above literature review reveals that there is no existing method for predicting the large-scale carbon intensity reduction potential of K-12 school buildings on a county-by-county basis. To fill the gap, this study investigates the large-scale carbon intensity reduction potential of K-12 school buildings on a county-by-county basis, which is not fully investigated yet. Furthermore, the new methods proposed in this paper can also be applied to any aggregated commercial buildings in the continental U.S. Based on the result of building energy modeling, the dynamic carbon emission factor of electricity is used to explore the carbon intensity reduction potential of commercial buildings on a county-by-county basis in the continental U.S. Then, to calculate the aggregated carbon intensity reduction of commercial buildings, the weighting values of floor area calculated from the existing construction database are considered. According to the research objective, this study adopts this method to comprehensively assess the carbon intensity reduction potential of K-12 school buildings in the continental U.S. on a county-by-county basis.

The rest of this paper is organized as follows: Section 2 introduces the methodology of predicting county-by-county based carbon intensity reduction potential of aggregated commercial buildings; Section 3 describes the application of this method in K-12 school buildings including building energy model preparation, information on building locations, building retrofit measures and weighting values of floor area between primary and secondary school buildings; Section 4 presents the results of carbon intensity reduction of K-12 school buildings; Section 5 discusses the spatiotemporal variability of the long-term carbon intensity reduction of K-12 school buildings. Finally, Section 6 concludes and discusses future work.

2 Methodology

This study develops a method to comprehensively assess the long-term carbon intensity reduction potential of aggregated commercial buildings in the continental U.S. at the county level, as shown in Figure 1: (1) energy prediction for a commercial building, (2) carbon emission prediction for a commercial building, and (3) carbon intensity reduction potential of aggregated commercial buildings. Following these three steps, the carbon intensity reduction potential of aggregated commercial buildings within a county with specific retrofit measure in a certain year can be predicted. Subsections 2.1, 2.2, and 2.3 introduce these three steps in detail.

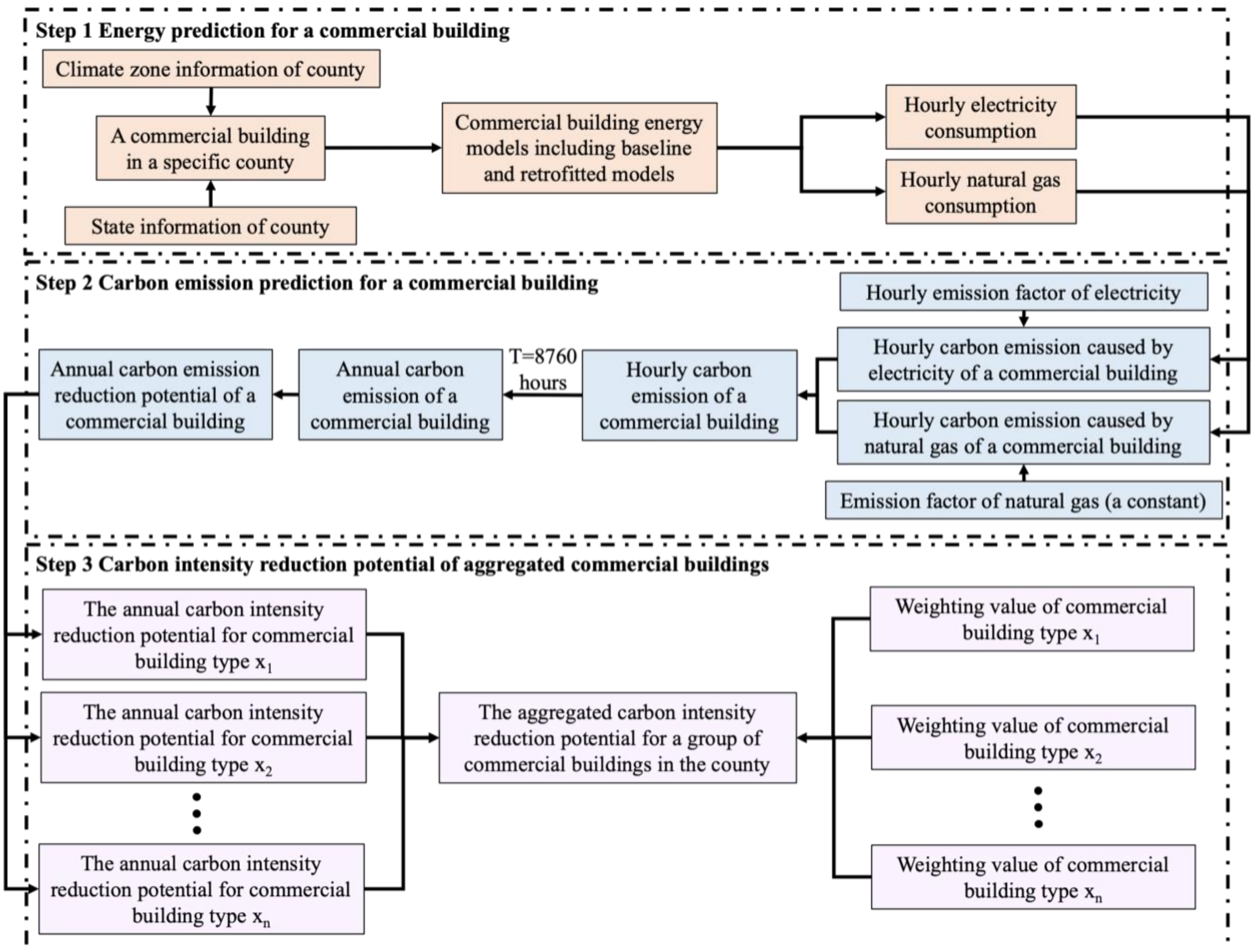


Figure 1. Method to predict carbon intensity reduction of aggregated commercial building in a county

2.1 Energy prediction for a commercial building

Building America determines building practices based on climate zones to achieve the most energy-efficient buildings [31]. Counties in one climate zone share the same climate feature. Thus, we assume that the energy usages of commercial buildings in one climate zone are the same. This study predicts energy consumption for baseline buildings and retrofit buildings by adopting individual measures in 14 climate zones in the U.S. It is worthwhile to mention that this study focuses on existing commercial buildings, and the study predicts the carbon intensity reduction potential for the existing commercial buildings from 2022 to 2050. Since electricity and natural gas account for 93% of the energy sources used in existing commercial buildings in the U.S., we only consider these two to predict the energy consumption of buildings [32]. Therefore, in the annual energy modeling, energy consumption can be divided into two parts: (1) electricity consumption and (2) natural gas consumption. To predict the carbon intensity reduction potential, we adopt the dynamic carbon emission factor of electricity from an open-sourced tool Cambium [33]. The data in Cambium is created using 2012 weather patterns, which influence electricity demand shapes and renewable energy resource quality. To avoid inaccuracies caused by the misalignment of assumptions, we use the 2012 weather as the building energy modeling inputs, which is highly recommended by the Cambium developer when using the hourly data [34]. Then, the electricity and natural gas consumptions simulated by 2012 AMY data are used for the prediction of carbon intensity reduction from the year 2022 to the year 2050 in this study.

2.2 Carbon emission prediction for a commercial building

For a building b_{x_1} belonging to the specific building type x_1, it is in a county within state s and from climate zone c. Then, the carbon emissions of this building with an individual retrofit measure i in the year j can be obtained using the following formula:

$$\begin{aligned} C_{b_{x_1},s,c,i,j} &= \sum_{t=1}^{T} C_{b_{x_1},s,c,i,j,t} = \sum_{t=1}^{T}(Ce_{b_{x_1},s,c,i,j,t} + Cn_{b_{x_1},s,c,i,t}) \\ &= \sum_{t=1}^{T}(E_{b_{x_1},s,c,i,j,t} \times \varepsilon e_{s,j,t} + N_{b_{x_1},s,c,i,j,t} \times \varepsilon n), \end{aligned} \tag{1}$$

where, the t represents one hour; the T is the total number of hours in a year, which is 8760 hours; the C represents carbon emissions; the Ce represents carbon emissions generated by electricity; the Cn represents carbon emissions generated by natural gas; the E represents the electricity consumption; the εe represents the electricity emission factor; the N represents the natural gas consumption, and the εn represents the natural gas emission factor.

Using equation (1), we can get the carbon emissions of a building $C_{b_{x_1},s,c,i,j}$.The data sources for emission prediction are explained as follows: (1) hourly electricity consumption ($E_{b_{x_1},s,c,i,j,t}$) and hourly natural gas consumption ($N_{b_{x_1},s,c,i,j,t}$) are obtained from subsection 2.1; (2) electricity carbon emission factors ($\varepsilon e_{s,j,t}$) are obtained from the National Renewable Energy Laboratory (NREL) Cambium tool [33]; and (3) natural gas emission factor (εn) is a constant, which is 50.15 kg/GJ [35].

2.3 Carbon intensity prediction of aggregated commercial buildings

2.3.1 Weighting value calculation

From subsections 2.1 and 2.2, we obtain the carbon emission of buildings with retrofit measures. Then, the aggregated carbon intensity reduction of a group of commercial buildings $(x_1, x_2, \cdots x_n)$ for a county can be calculated by the weighting value. In this study, the building type is identified with the building's function such as medium office, or hotel. Other building types can refer to the DOE prototype buildings [36]. The construction year of building is not considered due to the limited dataset access. For the building type x_1 within the state s and climate zone c, the weighting value for this specific building type $w_{x_1,s,c}$ can be calculated by the following formula:

$$w_{x_1,s,c} = \frac{A_{x_1,s,c}}{A_{x_1,s,c} + A_{x_2,s,c} + \cdots + A_{n,s,c}}, \tag{2}$$

where, the $A_{x_1,s,c}$ is the total floor area of commercial building type x_1 within the state s and climate zone c, To acquire the floor area information, there are many databases including the construction information of commercial buildings that can be adopted to calculate the weighting factor by using equation (2). For example, the Pacific Northwest National Laboratory (PNNL) evaluated weighting factors w for the national commercial building construction of each the climate zone in the U.S. based on the McGraw Hill Construction Database [37].

2.3.2 Carbon intensity reduction of aggregated commercial buildings

From subsection 2.2, we predict the carbon emission reduction of commercial buildings. Then, the carbon intensity reduction by retrofit measure i commercial building b_{x_1} $(\rho_{b_{x_1},s,c,i})$ can be calculated by the following equation:

$$\rho_{b_{x_1},s,c,i} = \frac{C_{b_{x_1},s,c,0,j} - C_{b_{x_1},s,c,i,j}}{F_{b_{x_1}}}, \tag{3}$$

where, the F_{bx_1} is the floor area of a commercial building b_{x_1}; the building is in the state s and from climate zone c; the $C_{b_{x_1},s,c,0,j}$ represents carbon emission of the bassline commercial building model in the year j; and the $C_{b_{x_1},s,c,i,j}$ represents carbon emission of the retrofitted commercial building with the retrofit measure i in the year j. Due to the similar building characteristics for a specific building type, the carbon intensity reduction of building type x_1 can be obtained from the following equation:

$$\rho_{x_1,s,c,i} = \rho_{b_{x_1},s,c,i}, \tag{4}$$

The carbon intensity reduction of other building types can be obtained by equations (3) and (4). Then, the aggregated carbon reduction intensity of group of commercial buildings $(\rho_{x_1+x_2+\cdots+x_n,s,c,i})$ can be acquired by the following equation:

$$\rho_{x_1+x_2+\cdots+x_n,s,c,i} = w_{x_1,s,c} \times \rho_{x_1,s,c,i} + w_{x_2,s,c} \times \rho_{x_2,s,c,i} + \cdots + w_{x_n,s,c} \times \rho_{x_n,s,c,i} \tag{5}$$

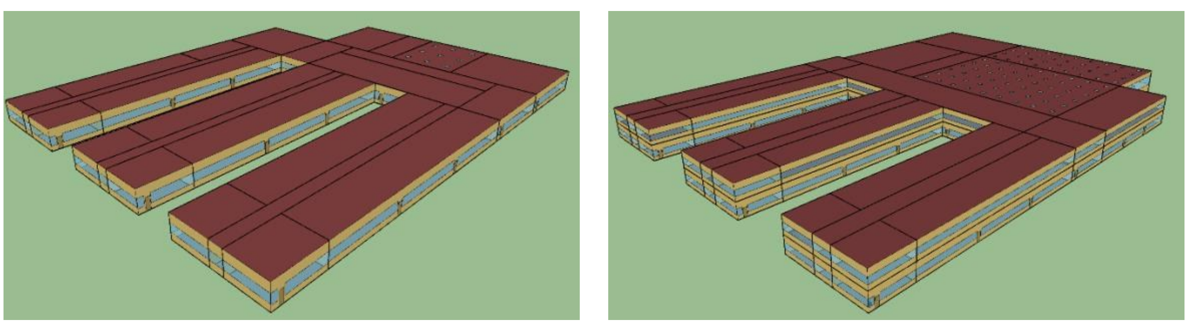
where $x_1, x_2, \cdots, x_n$ represent the different commercial building types; for example, $w_{x_1,s,c}$ is the weighting value of floor area for a building type x_1 in state s and climate zone c. The $\rho_{x_1,s,c}$ is the carbon intensity reduction of specific building type x_1 in state s and climate zone c, which are calculated using equation (3).

3 Study Design

According to the method developed in section 2, we select the K-12 school building as an application of this method. This section provides the overview of K-12 school buildings energy model including primary and secondary school building models, weather features for simulation, values for building retrofit measures, and the weighting value to calculate the aggregated carbon intensity reduction.

3.1 Building energy model

To provide a baseline and quantify the carbon intensity reduction of K-12 school buildings, two DOE prototype building energy models were adopted [36]. These two models are based on the national commercial building energy code ASHRAE Standard 90.1-2007 [38]. Generally, commercial buildings in each state are based on the state commercial building energy code and some cities even have city building energy codes. For example, Boulder, as a city in the state of Colorado, has the city building energy code. Even though we know the construction year of K-12 school buildings, it is hard to identify which building energy code the building within a county is used, more than this, the K-12 school buildings might even have building retrofits, then, the building energy performance would be different compared with the building energy code. Since this study aims to analyze the average level of large-scale carbon intensity in the United States, the building energy models based on the national commercial building energy code are adopted to make the assessment more feasible. Moreover, considering the construction year of K-12 school buildings in the U.S. and the adoption lag of the building energy code, the school building energy models based on ASHRAE Standard 90.1-2007 are adopted [4,39]. The geometry models of school buildings are shown in Figure 2.



(a) Primary school (b) Secondary school

Figure 2. The geometry of school buildings

The primary school building is divided into 25 thermal zones, and has one story, with a 6,872 m^2 floor area and a 35% window-to-wall ratio. The secondary school building is divided into 46 thermal zones, and has two stories, with a 19,594 m^2 floor area and a 33% window-to-wall ratio. Both buildings have steel-frame exterior walls and built-up roofs with insulation layers. The HVAC system in the primary school building includes gas furnaces, gas boilers, packaged air conditioning units, and VAV terminal boxes. Compared with the primary school building, the secondary school building has one more air-cooled chiller in the HVAC system. According to the CBECS data, natural gas is consumed most for space heating [9]. Then, the energy sources of these buildings can be divided into two types. Electricity is consumed for AC cooling and reheating, lighting, and plug loads, and natural gas is used for AC heating and service water heating. These building models include a primary school and secondary school, each of which is carefully assembled to be representative of construction for K-12 school buildings of its class. The space types included in each prototype design are shown in Table 1.

Table 1. Space types of school buildings

Space type	Area in Primary school (m^2)	Area in Secondary school (m^2)
Auditorium	NA	988
Cafeteria	315	624
Classroom	3,456	6,913
Corridor	1,122	4,200
Gymnasium	357	3,224
Kitchen	168	216
Library	399	840
Lobby	171	420
Mechanical/Electrical/Telecom Room	252	684
Office	441	1,064
Restroom	190	420

3.2 Locations

This research focuses on the carbon intensity reduction of 14 climate zones in the continental U.S., which excludes Hawaii and Alaska. The characterization of these climate zones is based on seasonal performance metrics and not on peak or design values. According to the 2012 International Energy Conservation Code (IECC) [40], each climate zone is clustered by HDD65 for the heating and CDD50 for the cooling and further subdivided by moisture levels as humid (A), dry (B), and marine (C) to characterize their seasonal values. The distribution of climate zones is based on the 2012 IECC, then fourteen cities have been identified as sufficient to represent all the regions in the climate zones according to the Building Energy Codes Program of the Department of Energy [36], as shown in Figure 3. The summary of fourteen representative cities and their climate feature is shown in Table 2.

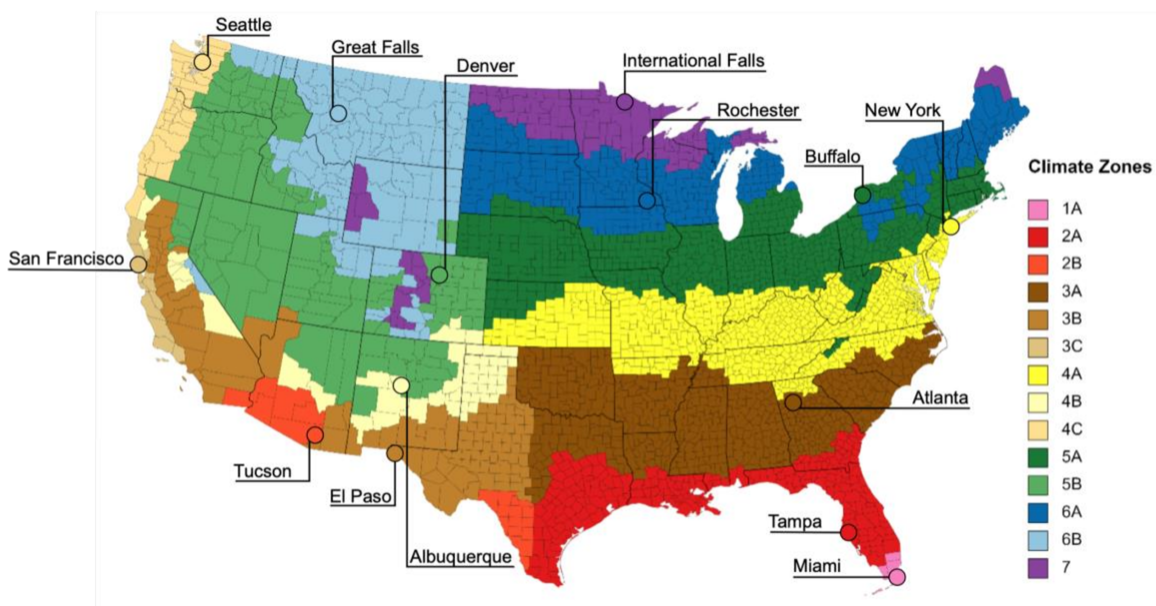


Figure 3. International Energy Conservation Code (IECC) climate zones [40]

Table 2. Cities characterized by climate combinations

	Hot	Mild	Cold	Very Cold
Humid	Miami-1A Tampa-2A Atlanta-3A	New York-4A	Buffalo-5A Rochester-6A	
Dry	Tucson-2B El Paso-3B	Albuquerque-4B	Denver-5B Great Falls-6B	International Falls-7
Marine		San Francisco-3C Seattle-4C		

3.3 Building retrofit measures

There are many building retrofit measures available for commercial buildings [41–46]. This research selects eight building retrofit measures as input variables of building energy models. The eight building retrofit measures and their values are shown in Table 3. The values vary by the different climate feature locations. Furthermore, the building model to calculate the aggregated effect of these eight measures is built. The abbreviation ALL is used to represent the aggregated effect of these eight measures. The combination of eight measures results in 280 building energy models (2 building type × 14 locations × (1 baseline model + 9 retrofit models)). The model input values of baseline models are based on ASHRAE Standard 90.1-2007 [38]. The model input values of retrofit models in 14 climate zones are referred from the Advanced Energy Design Guide for K-12 school buildings 50% Energy Savings [47].

For the suggested retrofitted value, detailed upgrading strategies could be found in AEDG for K-12 school buildings with 50% Energy Savings. For example, the roof insulation can be increased by installing continuous insulation at the bottom of the rafters and above the ceiling material; the wall thermal performance of steel-framed walls can be upgraded by adding exterior foam sheathing without degrading by the thermal bridges; the window thermal performance can be improved via replacing the single pane windows with double glazing windows or adding insulated blind systems; lighting power density could be lowered by replacing incandescent lamps with light-emitting diodes (LED); the plug load density can be reduced by implementing sleep mode software on the desktop computer; the cooling and heating equipment efficiencies can be improved by replacing higher efficiency equipment; the efficiency of service hot water system can be improved by replacing condensing gas storage water heaters with gas-fired instantaneous water heaters [47].

Table 3. Building retrofit measures and values

Building Retrofit Measure	Abbreviation	Model Input	Building Types	1A		2A		2B		3A		3B		3C		4A		4B		4C		5A		5B		6A		6B		7	
				Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]
Add wall insulation	WALL	Wall insulation R-value (m2-K/W)	Primary & Secondary School	1.04	1.04	1.04	1.34	1.04	1.34	1.71	2.01	1.71	2.01	1.71	2.01	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37	2.37
Add roof insulation	ROOF	Roof insulation R-value (m2-K/W)	Primary & Secondary School	2.60	3.52	3.47	4.41	3.47	4.41	3.47	4.41	3.47	4.41	3.47	4.41	3.47	5.29	3.47	5.29	3.47	5.29	3.47	5.29	3.47	5.29	3.47	5.29	3.47	5.29	3.47	5.29
Replace windows	WINDOW	Window U-factor (W/m2-K)	Primary & Secondary School	6.82	3.18	4.09	2.56	4.09	2.56	3.52	2.33	3.52	2.33	3.52	2.16	2.90	2.16	2.90	2.16	2.90	2.16	2.73	2.16	2.73	1.99	2.73	1.99	2.73	1.99	2.73	1.99
		Window SHGC		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.42	0.40	0.42	0.40	0.42	0.40	0.42	0.40	0.42
Improve lighting efficiency	LIGHT	Lighting power density (W/m2)	Primary School	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53	12.80	7.53
			Secondary School	12.16		12.16		12.16		12.16		12.16		12.16		12.16		12.16		12.16		12.16		12.16		12.16		12.16		12.16	
Improve equipment efficiency (excluded kitchen)	EQUIP	Plug load density (W/m2)	Primary School	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04	12.16	8.04
			Secondary School	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84	11.51	5.84
Improve cooling coil efficiency	COOLING	Nominal coefficient of performance	Primary & Secondary School	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37
Improve heating efficiency	HEATING	Burner efficiency	Primary & Secondary School	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90
Improve service hot water system efficiency	SWH	Heater thermal efficiency	Primary & Secondary School	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95	0.81	0.95

[1] Base: Baseline model (Source: ASHRAE Standard 90.1–2007 [38])
[2] Retr: Retrofit model (Source: AEDG K-12 school buildings 50% Energy Savings [47])

3.4 Weighting value between primary school and secondary school

According to PNNL's research outcomes based on the McGraw Hill Construction Database [37], we remapped the weighting factors between primary school and secondary school in the continental U.S., as shown in Table 4. Ideally, the total carbon emission reduction can be predicted with the weighting value including both state and climate zone geometrical information. However, the data access limits the obtaining of weighting value including the state information. Therefore, this study adopts the weighting value with climate zone information to predict the aggregated carbon reduction intensity of K-12 school buildings.

Table 4. Remapping the weighting value of K-12 buildings in the continental US

Climate Zone	**1A**	**2A**	**2B**	**3A**	**3B**	**3C**	**4A**
Primary School	28%	42%	38%	35%	30%	33%	32%
Secondary School	72%	58%	62%	65%	70%	67%	68%
Climate Zone	**4B**	**4C**	**5A**	**5B**	**6A**	**6B**	**7**
Primary School	28%	31%	34%	29%	30%	29%	24%
Secondary School	72%	69%	66%	71%	70%	71%	76%

4 Results

With the section 2 methodology and section 3 study design, the energy use intensity (EUI) reduction of K-12 school buildings by adopting the building retrofit measures can be predicted. Then the long-term carbon intensity reduction potential of K-12 school buildings in the U.S. is predicted on a county-by-county basis.

4.1 Energy use intensity (EUI) prediction

With the eight building retrofit measures, we simulate the energy consumption and calculate the EUI reduction of K-12 school buildings for each county in the continental U.S., as shown in Figure 4. It indicates that the EUI reduction of K-12 school buildings in the 14 climate zones will range from 123 MJ/m^2-yr to 203 MJ/m^2-yr. For the energy-saving analysis, the simulation is based on climate features. The value of EUI reduction is related to climate features instead of state because a state may include various climate features. For example, the counties in Taxes have several climate features (e.g., hot humid, mild dry). The simulation result shows that the areas with the relatively highest EUI reduction will concentrate in hot humid (e.g., Florida, Texas) and cold humid climate zones (e.g., Michigan, Minnesota). The areas with the relatively lowest EUI reduction will concentrate on the west coast of the U.S., and the climate features are mild marine (e.g., Washington) and hot dry (e.g., Arizona).

According to the 2012 and 2018 Commercial Building Energy Consumption Survey, the growth rate of total commercial building floorspace from 2012 to 2018 in the U.S. is 11%[9]. Referring to the Total Energy Annual Data from U.S. Energy Information Administration, the growth rate of commercial sector energy consumption from 2012 to 2018 is 14% [48]. Therefore, we assume the energy use intensity (EUI) will not change significantly from 2022 to 2050.

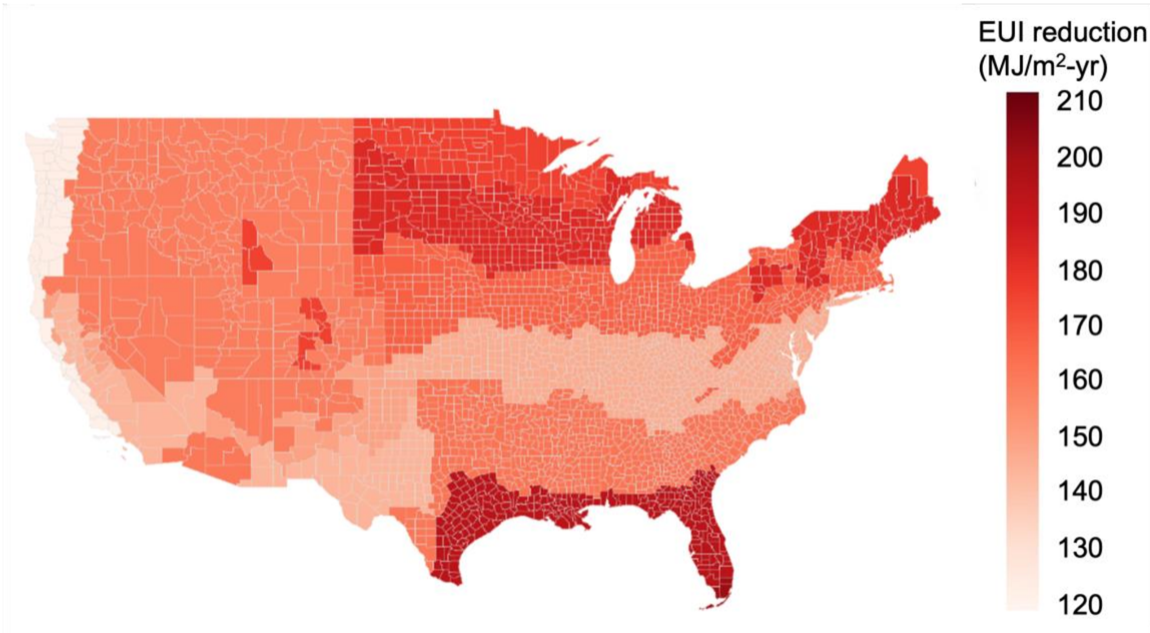


Figure 4. Annual EUI reduction potential of K-12 school buildings with retrofit measure ALL

4.2 The long-term carbon intensity reduction potential

Based on the method introduced in subsections 2.2 and 2.3, the long-term carbon intensity reductions of K-12 school buildings with different retrofit measures from 2022 to 2050 are calculated. Retrofit measure ALL is used as an example to illustrate the long-term carbon intensity reductions, as shown in Figure 5. The carbon emission of the baseline model is also presented in Appendix A, Table A. 1. Figure 5 shows that the carbon intensity reduction potential will decrease over time, and the range of carbon reduction will also decrease, which is similar to existing research of medium offices. That study adopted the dynamic electricity emission factor to predict the carbon emission of medium offices and they found that the carbon emission reduction potential will decrease over time [12]. As shown in Figure 5, the difference in color will become smaller over time due to the adoption of the dynamic electricity emission factor.

For example, the result shows the range of carbon intensity reduction potential in 2022 will be from 1.66 kg/m^2-yr to 40.00 kg/m^2-yr, and the range in 2050 will be from 0.41 kg/m^2-yr to 18.69 kg/m^2-yr. As we mentioned in subsection 3.2, the energy usage of the school building is assumed to be constant within one climate zone. However, the value and trend of carbon intensity reduction in each state will be different when the EUI is the same.

Figure 5 shows that in the cold climate zones (5A, 5B, 6A, 6B, 7), the average carbon intensity reduction potential is higher than the average carbon intensity reduction potential in hot climate zones. This is because the buildings in the cold climate zone have a high demand for heating during the long and cold winter and natural gas is used for heating [33,49]. The higher demand for dirty energy sources leads to higher carbon emissions. Therefore, the cold climate zones have a higher average carbon intensity reduction potential than hot climate zones. The following subsections present the result of the carbon intensity reduction potential of K-12 school buildings with retrofit measures ALL in three different climate zones.

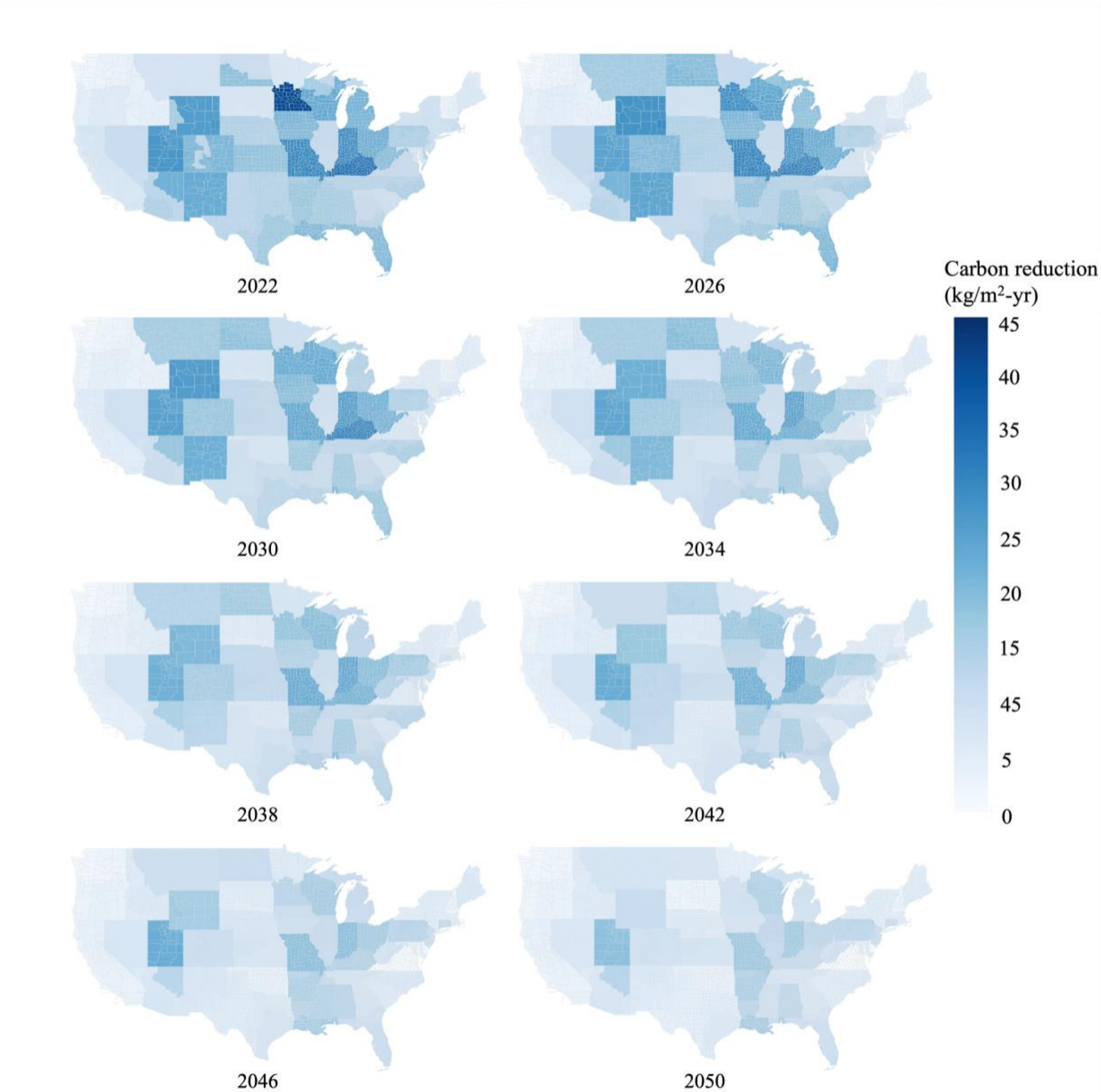


Figure 5. Annual carbon intensity reduction potential in the continental U.S. from 2022 to 2050

4.2.1 Carbon intensity reduction potential in hot climate zone

The climate feature of zone 2A is hot and humid. The counties in climate zone 2A are from the states of Alabama, Florida, Georgia, Louisiana, Mississippi, and Texas. The annual carbon intensity reduction potential of these counties from 2022 to 2050 is shown in Figure 6. We group the counties by their state. The general trend is that the carbon intensity reduction potential decreases over time. To achieve the low-carbon development goals, clean energy penetration will increase over time. With higher clean energy penetration, the building will consume fewer dirty energy sources and emit less carbon, and thus, the carbon intensity reduction potential will decrease.

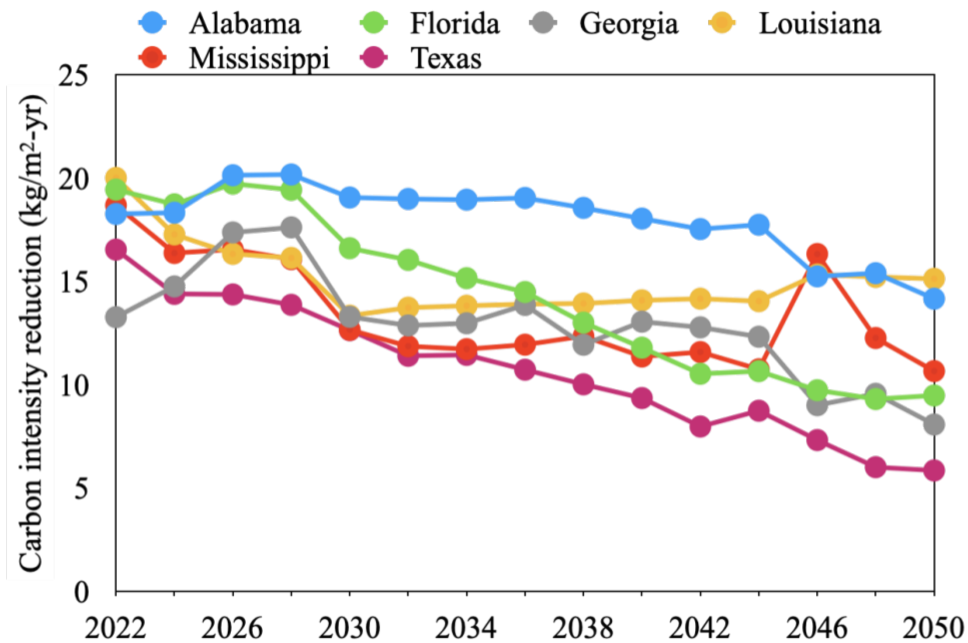


Figure 6. Annual carbon intensity reduction potential in climate zone 2A (hot humid) from 2022 to 2050

However, it is worth mentioning that the carbon intensity reduction potential does not reduce all the time. It is caused by the change of electricity source. According to the definition stated by the DOE [50], clean energy includes solar, wind, water, geothermal, bioenergy, and nuclear. Then, all the clean energy sources are combined into a group by this definition. Take the counties in Mississippi as an example, it indicates that there will be an obvious protrude from 2044 to 2046, and the carbon intensity reduction will increase abruptly in 2046, as shown in Figure 6. As shown in Figure 7, from 2044 to 2046, the clean energy penetration will decrease, and the percentage of dirty energy consumption will increase. When consuming the same energy, it will consume more dirty energy sources. Therefore, the reduction potential of carbon intensity will increase when saving the same amount of energy. The reason for the significant gap is that the license of Grand Gulf Nuclear Station in Mississippi will end in 2044. After 2044, the supply of nuclear energy is supposed to be replaced by natural gas and coal-fired power plants.

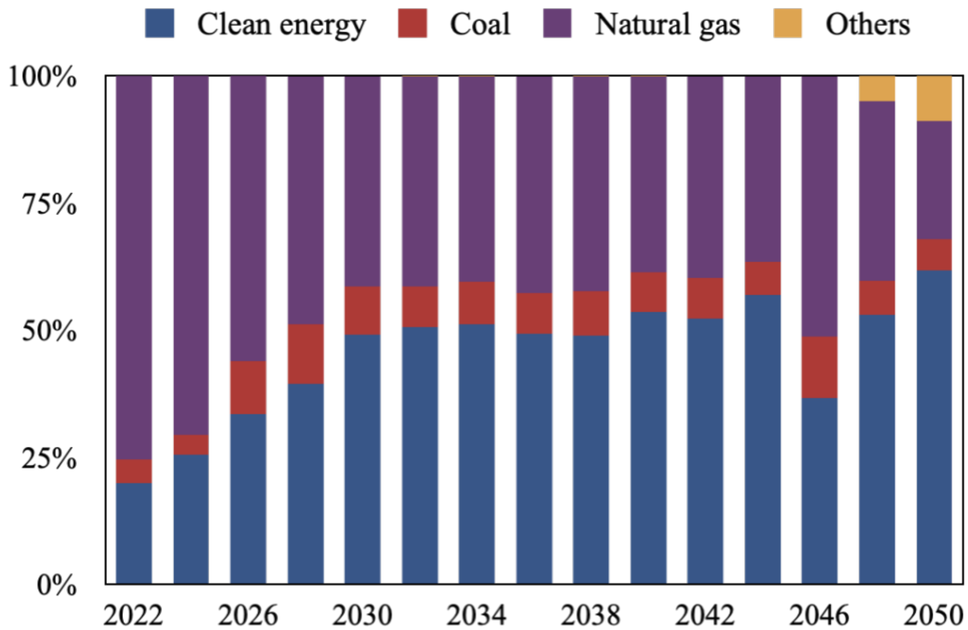


Figure 7. Electricity source change in the counties from Mississippi in climate zone 2A

4.2.2 Carbon intensity reduction potential in mild climate zone

The climate feature of zone 4C is identified as mild and marine. The counties in climate zone 4C are from the states of Washington, California, and Oregon. As shown in Figure 8, the annual carbon intensity reduction potential in the counties of California and Oregon will decrease from 2022 to 2050. However, for the counties in Washington, the carbon intensity reduction potential will not change significantly over time, and the value of carbon intensity reduction is always the lowest in zone 4C. It is because the energy source structure of Washington does not change too much from 2022 to 2050 and the energy source of Washington is cleaner compared with others. As shown in Figure 9, Washington always keeps on a high clean energy penetration which is more than 75%. Dehdar et al. indicated that Washington state has always depended on hydropower generation and after adding wind capacity the state achieved 96 billion kWh of non-carbon electric generation in the year 2016 [51]. Therefore, Washington has such low carbon intensity reduction among the others in climate zone 4C.

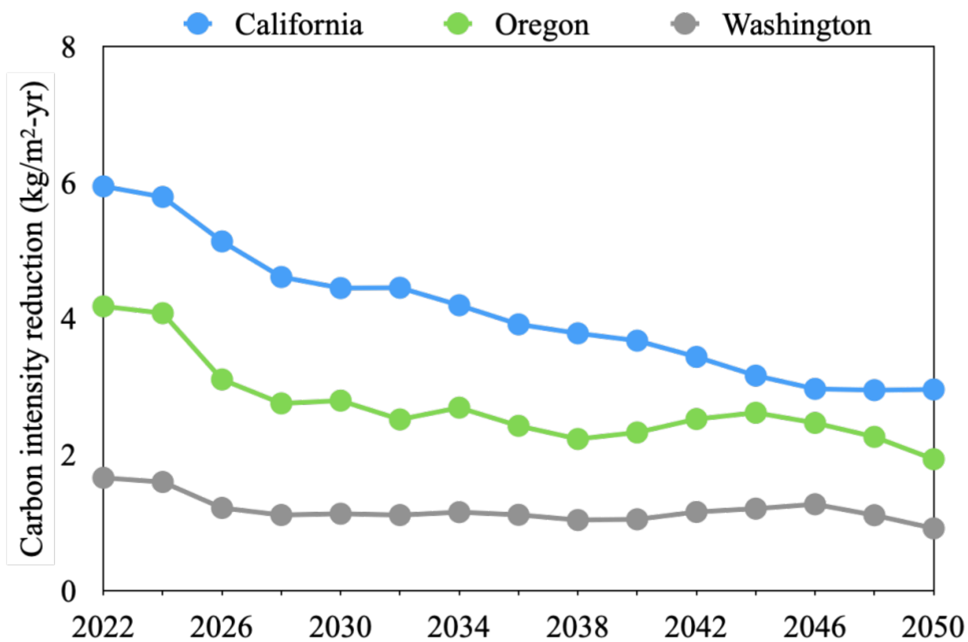


Figure 8. Annual carbon intensity reduction potential in climate zone 4C (mild marine) from 2022 to 2050

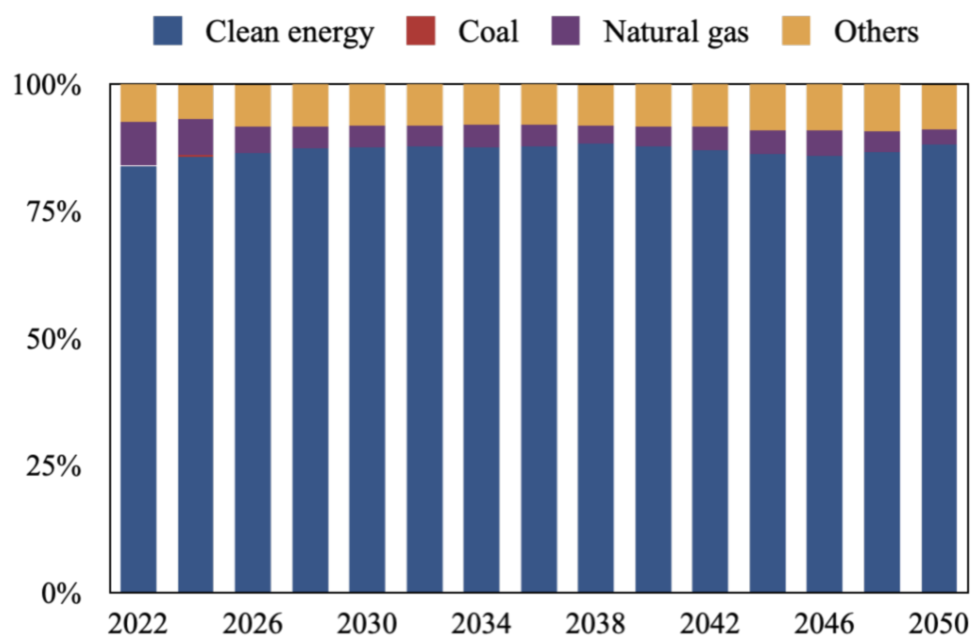


Figure 9. Electricity source change in the counties from Washington in climate zone 4C

4.2.3 Carbon intensity reduction potential in cold climate zone

The climate feature of zone 6B is cold and dry. The counties in climate zone 6B are from the states of California, Colorado, Idaho, Montana, Utah, Washington, and Wyoming. As shown in Figure 10, in Idaho, the annual carbon intensity reduction potential will increase from 2032 to 2036. It is because the clean energy penetration of Idaho will decrease from 2032 to 2036, as shown in Figure 11 (a). In Montana, the carbon intensity reduction potential will increase from the year 2022 to 2026, it is because the clean energy penetration will decrease from 2022 to 2026, as shown in Figure 11 (b). The examples of Idaho and Montana illustrate the relationship between the carbon intensity reduction potential and clean energy penetration.

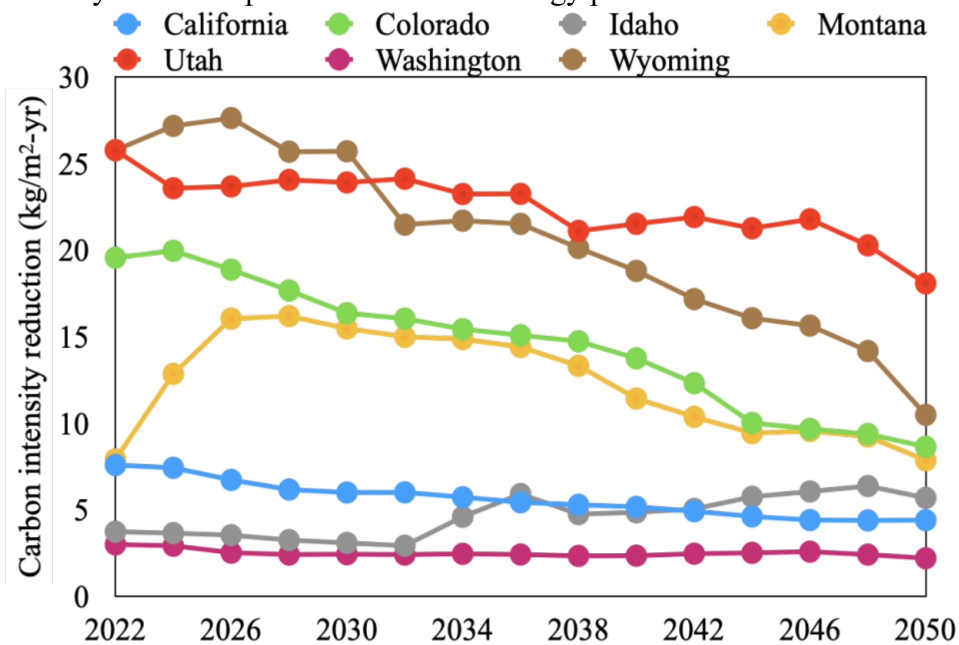


Figure 10. Annual carbon intensity reduction potential in climate zone 6B (Cold Dry) from 2022 to 2050

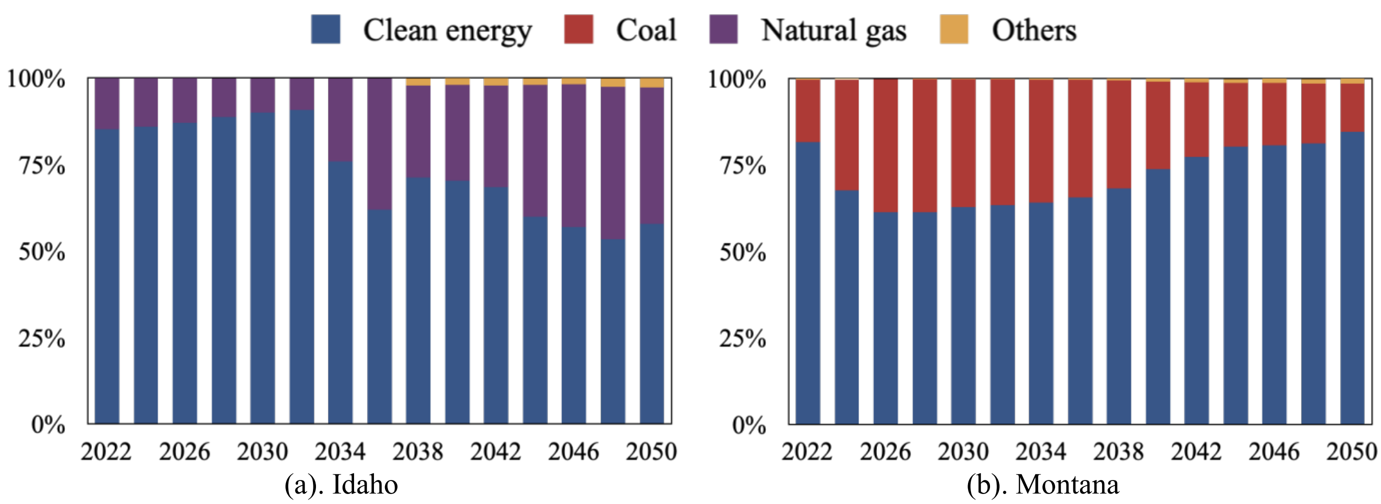


Figure 11. Electricity source change in the counties from Idaho and Montana of climate zone 6B

5 Discussion

5.1 Comparison of U.S. map from 2022 to 2050

In subsection 4.2, the large-scale carbon intensity reduction potential has been shown on a county-by-county basis. This section further discusses the change of large-scale carbon intensity reduction from 2022 to 2050.

5.1.1 Long-term change of carbon intensity reduction for the measure ALL

Figure 5 shows the carbon intensity reduction in each county from 2022 to 2050. The carbon reduction will decrease year by year. Moreover, in subsection 4.3, the relevance between the carbon intensity reduction potential and the clean energy penetration is analyzed. Therefore, it not only indicates the change in carbon reduction but also the penetration of clean energy. To verify the relevance between the carbon intensity reduction potential and clean energy penetration, the annual penetration of clean energy on a county-by-county basis is shown in Figure 12.

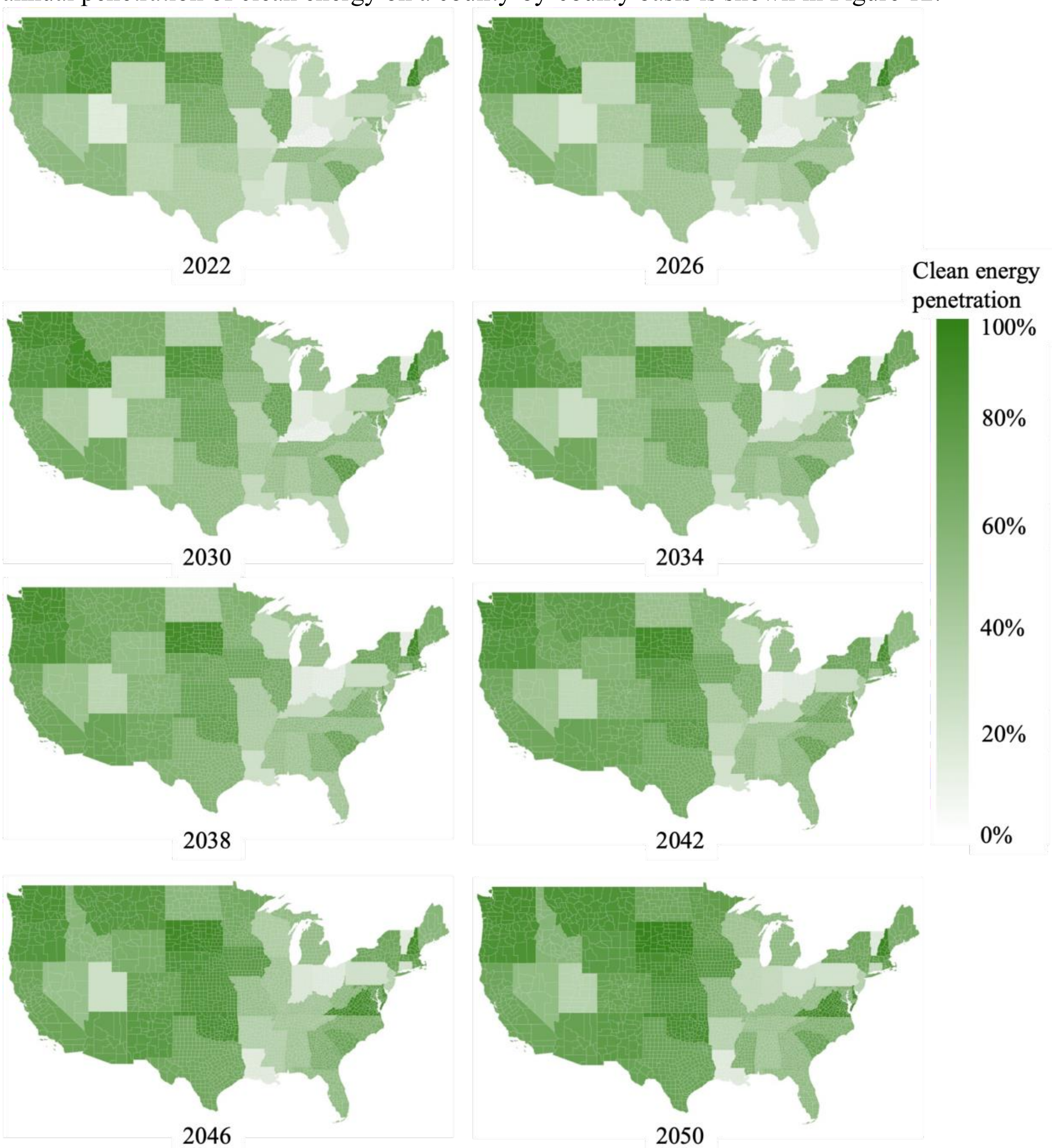


Figure 12. Annual penetration of clean energy in the continental U.S. from 2022 to 2050

Different from the U.S. map in Figure 5, the color of the U.S. map in Figure 12 gradually becomes dark, which represents the increasing clean energy penetration. With the clean energy penetration increasing, dirty energy consumption reduces when the energy use intensity is relatively constant. Less dirty energy consumption leads to fewer carbon emissions. Then, the carbon intensity decreases as a result, and the room for decreasing carbon intensity becomes small. In other words, the carbon reduction potential will gradually become small over time.

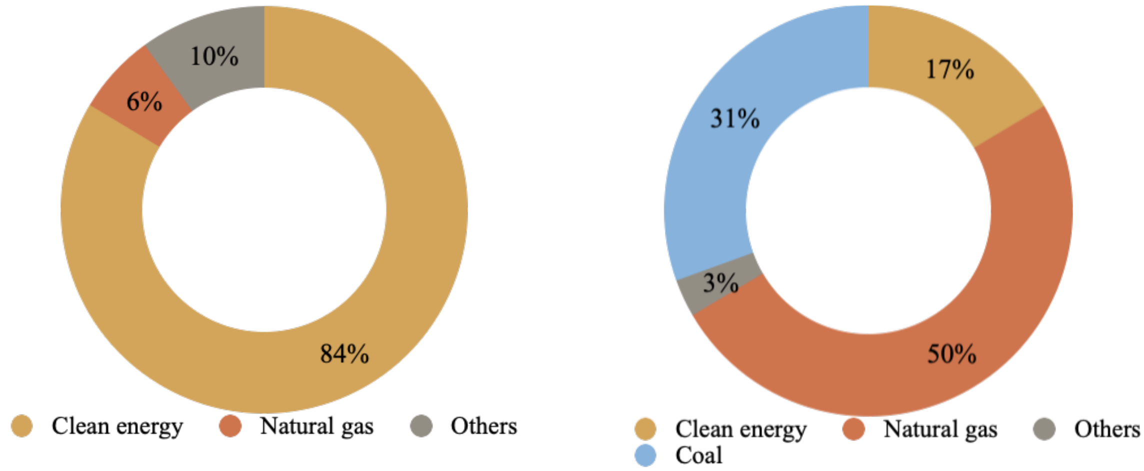
5.1.2 Impact of electricity structure

The carbon intensity reduction potential of the retrofitted building model is relevant to the electricity source structure. After using the building retrofit, we assume that the energy saving is the same within one climate zone, but the carbon intensity reduction varied a lot, as shown in Figure 5. Table 5 shows the highest and lowest carbon intensity reduction potential counties, and the information in the table is simplified into their state and climate zone information.

Table 5. The highest and lowest carbon intensity reduction potential states from 2022 to 2050

Year	The highest three annual carbon intensity reduction potential regions (State – climate zone)	The lowest three annual carbon intensity reduction potential regions (State – climate zone)
2022	Minnesota - 6A, Kentucky - 4A, Missouri - 4A	Washington - 4C, Vermont - 6A, Washington - 5B
2026	Kentucky - 4A, Missouri - 4A, Wyoming - 5B	Washington - 4C, Washington - 5B, New Hampshire - 5A
2030	Kentucky - 4A, Wyoming - 5B, Wyoming - 7	Washington - 4C, Washington - 5B, Vermont - 6A
2034	Indiana - 4A, Utah - 5B, Utah - 3B	Washington - 4C, Washington - 5B, Vermont - 6A
2038	Indiana - 4A, Indiana - 5A, Missouri - 4A	Washington - 4C, Washington - 5B, Oregon - 4C
2042	Indiana - 4A, Utah - 5B, Indiana - 5A	Washington - 4C, Washington - 5B, Oregon - 4C
2046	Utah - 5B, Indiana - 4A, Indiana - 5A	Virginia - 4A, Washington - 4C, Delaware - 4A
2050	Utah - 5B, Missouri - 4A, Missouri - 5A	Virginia - 4A, Washington - 4C, Delaware - 4A

Even though the counties are in the same climate zones, their carbon intensity reduction potential can vary since they locate in different states. Take the year 2046 as an instance, the counties from Delaware and Indiana are in the same climate zone 4A identified as humid and mild. However, the carbon intensity reduction potential is different, and the carbon intensity reduction potential is higher in the counties from Indiana. As shown in Figure 13, Delaware has a high penetration of clean energy, and Indiana has a high consumption of coal. Consequently, when consuming the same amount of energy, the building in Indiana would emit more carbon since 30% of the source is from coal, which means there is more room for Indiana to reduce the carbon intensity with energy savings by applying building retrofits.

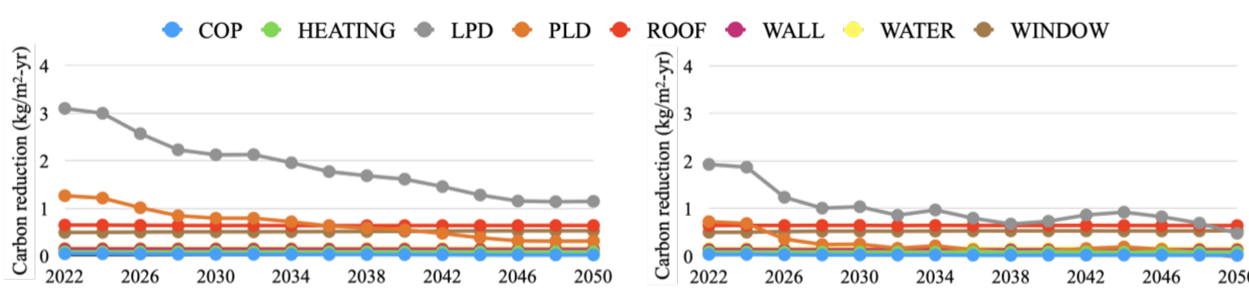


(a). Delaware (b). Indiana

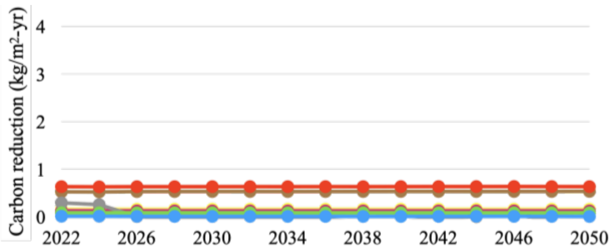
Figure 13. The energy source's structure for electricity generation of Delaware and Indiana states in 2046

5.2 Carbon intensity reduction potential with different retrofit measures

In subsection 4.2, the carbon intensity reductions of the retrofitted K-12 school buildings with eight measures in the counties from hot, mild, and cold climate zone are calculated. This section further explores the impacts of eight individual retrofit measures on the carbon intensity reduction potential of K-12 school buildings. Take climate zone 4C as an example. The counties in climate zone 4C are from three states. The carbon intensity reductions with eight measures of counties from three states are shown in Figure 14. In the counties from climate zone 4C, the retrofit measure with the most significant carbon intensity reduction potential is not the same. In counties of California, reducing the lighting power density has the most potential to reduce carbon intensity. However, in counties of Washington, increasing roof insulation has the most potential to reduce carbon intensity. Moreover, it is worth mentioning that, for the counties of Oregon, the retrofit measure with the most carbon intensity reduction potential is not always the same one, at the beginning, reducing the lighting power density can reduce the most carbon intensity, but it is replaced by increasing the roof insulation in 2050. This difference is because different retrofit measures have different impacts on energy reduction.



(a). California (b). Oregon

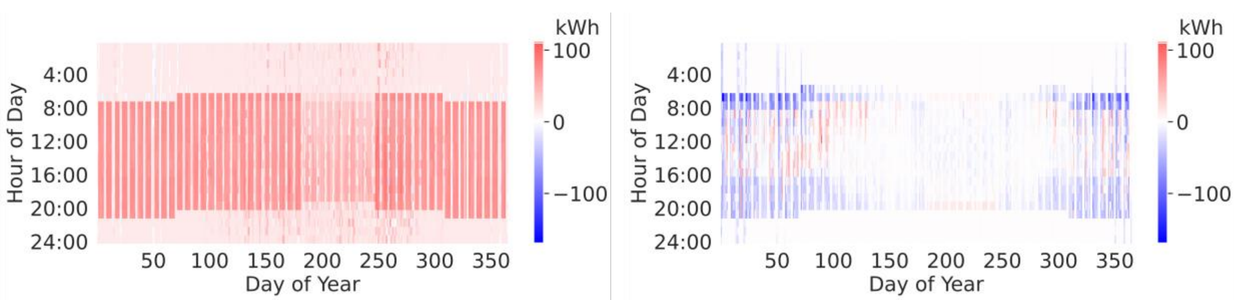


(c). Washington

Figure 14. Annual carbon intensity reduction of retrofitted K-12 school building in climate zone 4C

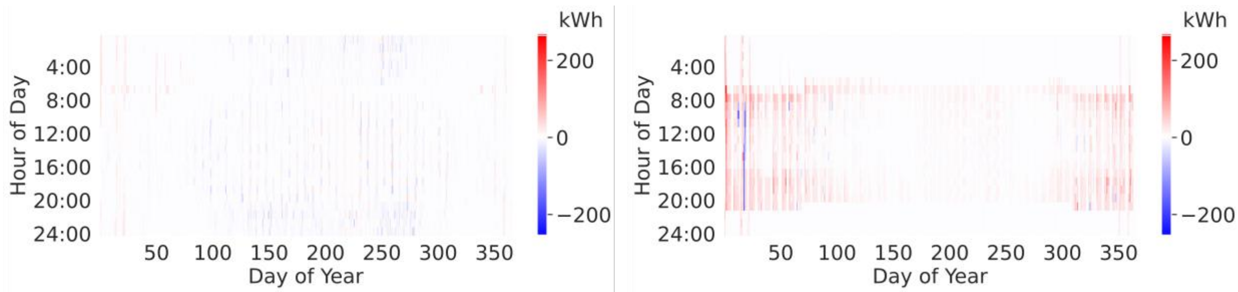
As shown in Figure 15, if we reduce the lighting power density, the electricity usage will decrease, and the natural gas consumption will increase. However, if we improve the roof insulation, the electricity usage will not change significantly, and the natural gas consumption will decrease, as shown in Figure 16. To calculate the carbon intensity reduction potential, we use the dynamic hourly emission factor for electricity generation, and for natural gas, it is a constant 50.15 kg/GJ. The electricity emission factor of California and Washington in 2030 is shown in Figure 17. For a clean state where the clean energy penetration is high and the electricity emission factor is relatively low (e.g., Washington), even reducing the lighting power density can reduce the electricity usage, and the carbon intensity caused by natural gas will offset it. Consequently, improving roof insulation becomes the most effective measure to reduce carbon intensity in Washington. For California, the emission factor of electricity is relatively high, so reducing the lighting power density can have the greatest carbon intensity reduction potential.

As for Oregon, in the beginning, reducing the lighting power density has the greatest potential to reduce carbon intensity. However, in the year 2050, increasing the insulation of the roof has more potential to reduce carbon intensity compared with reducing the lighting power density. This is led by the change in clean energy penetration. As shown in Figure 18, in 2022, the emission factor of electricity generation in Oregon is relatively high. However, it will drop rapidly in 2050 due to the increasing clean energy penetration. After offsetting the carbon intensity with natural gas, increasing the insulation of the roof has the greatest carbon intensity potential among the eight retrofit measures.



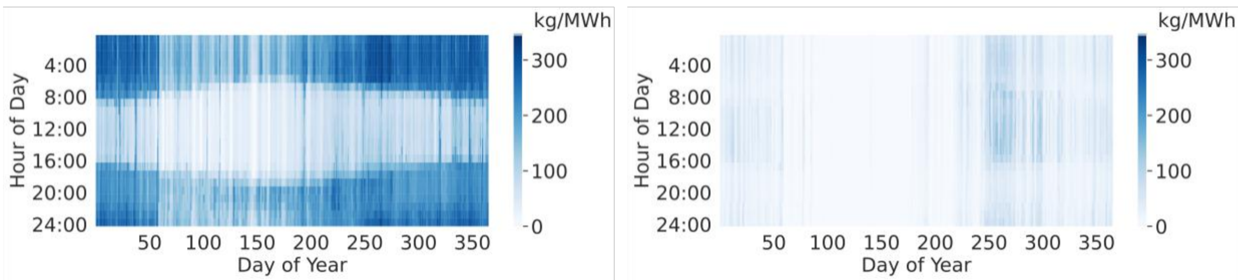
(a). Electricty reduction (b). Natural gas reduction

Figure 15. Energy reduction by reducing lighting power density



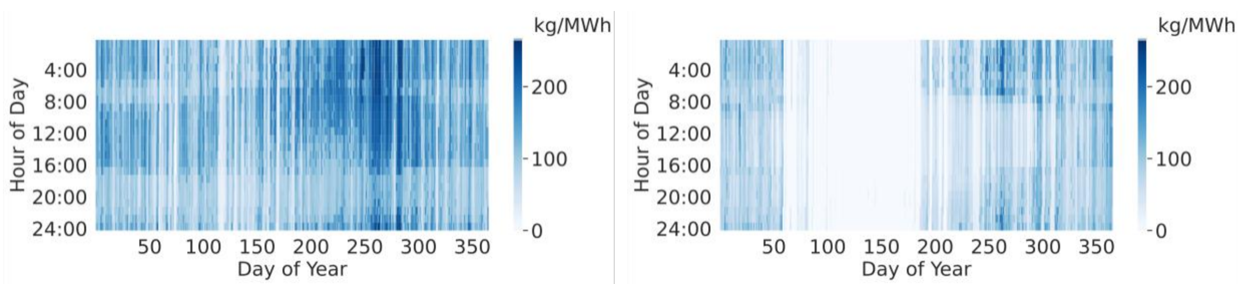
(a). Electricty reduction (b). Natural gas reduction

Figure 16. Energy reduction by increasing roof insulation



(a). California, 2030 (b). Washington, 2030

Figure 17. Carbon emission factor for electricity generation in 2030



(a). Oregon, 2022 (b). Oregon, 2050

Figure 18. Carbon emission factor for electricity generation in Oregon state

5.3 Future work for large scale carbon intensity assessment

This study builds a foundation for a platform that can evaluate carbon intensity reduction potential on a county-by-county basis. With the platform, the policymakers can estimate the impact of new technology or a policy on the carbon intensity of buildings. To improve this platform and make the results more realistic and representative in the future, more scenarios could be considered. For example, the building energy code for each building can be further investigated based on the city or state energy code, and the advanced retrofit measures can be considered with the breakthrough in building materials and other related fields. Also, another scenario about the cost of future energy sources, and the carbon tax can be considered for future study. Moreover, future weather changes can also be a potential impact factor on building carbon emissions. To sum up, with the proposed method in this study, a foundation of a platform can be built to estimate large-scale carbon intensity reduction of aggregated commercial buildings and be continuously developed for a more representative model. In the future, the experiment on commercial buildings can be feasible with the support from governmental institutions to validate the simulation result, further calibrate the model, and improve the performance of the platform. In this study, the K-12 school buildings are selected for the large-scale carbon intensity analysis. Therefore, the individual energy system consumed by natural gas and electricity is adopted in models. For future study, other energy systems can be considered for aggregated commercial buildings, such as the application of district heating and cooling systems in the university. To predict aggregated K-12 school buildings carbon intensity reduction, we refer to the weighting factor about the commercial building floor area from the technical report of PNNL. Ideally, the total mass of carbon emission reduction can be predicted with the weighting value including both state and climate zone geometrical information. However, the data access limits the obtaining of weighting value including the state information. Therefore, this study can only use the weighting value with climate zone information to predict aggregated carbon reduction intensity of K-12 school buildings. Later, if a better database is available, it can be used with the method developed in this research for more accurate large-scale prediction. Moreover, the carbon emission performance of building constructed in different years could be furthered analysis with a better informative database.

6 Conclusion

Based on the prediction of electricity sources in the next 30 years, this study develops a method to comprehensively assess the long-term carbon intensity reduction potential of aggregated commercial buildings in the continental U.S. at the county level. As an application of this method, this study investigates the county-by-county based (around 3000 counties) carbon intensity reduction of K-12 school buildings with eight building retrofits from 2022 to 2050 in the continental U.S. (excluding Hawaii and Alaska). From the long-term perspective, the carbon intensity reduction with building retrofits will decrease. The result shows that the carbon intensity reduction potential in 2022 at the county level ranges from 1.66 kg/m^2-yr to 40.00 kg/m^2-yr, and it ranges from 0.41 kg/m^2-yr to 18.69 kg/m^2-yr in 2050. However, the annual change in carbon intensity reduction depends on the adjustment of the electricity source. For example, the carbon intensity reduction in Mississippi state will increase abruptly from 2044 to 2046 since the supply of nuclear energy is supposed to be replaced by natural gas and coal-fired power plants with the license expiration of Grand Gulf Nuclear Station in Mississippi. Moreover, compared with the climate feature, which impacts the energy usage of the building, the electricity source has more impact on carbon intensity reduction. K-12 school buildings in a county with a higher clean energy penetration for electricity generation will have a lower carbon intensity reduction potential. In general, the measure of reducing lighting power density has the highest potential to decrease carbon intensity among the eight identified measures in most states. Adopting higher efficacy luminaires could be one of the effective methods to reduce the lighting power density and ensure indoor visual comfort. However, the situation may be changed due to the high clean energy penetration for electricity generation.

Acknowledgement

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Appendix A

Table A. 1 Carbon emission of baseline K-12 school building energy models (unit: ton)

Region (CZ-State)	Primary school								Secondary school							
	2022	2026	2030	2034	2038	2042	2046	2050	2022	2026	2030	2034	2038	2042	2046	2050
1A-FL	642.4	650.5	546.7	500.0	429.3	349.7	324.5	316.7	1780.4	1802.9	1519.7	1389.5	1195.0	973.2	901.2	878.7
1A-TX	553.2	480.7	422.4	383.7	337.7	271.5	251.3	203.9	1528.8	1327.7	1168.2	1060.2	932.2	748.4	691.2	558.3
2A-AL	569.0	622.5	588.9	586.0	586.0	542.2	473.9	441.6	1580.7	1729.2	1637.3	1629.3	1593.3	1507.3	1316.2	1224.7
2A-FL	603.1	609.1	509.9	467.0	467.0	322.9	299.0	292.2	1679.8	1695.2	1419.7	1299.8	1107.0	894.0	825.6	805.8
2A-GA	420.5	543.1	415.8	405.7	405.7	396.1	282.3	255.3	1168.6	1511.7	1155.9	1127.0	1031.5	1098.7	777.2	700.8
2A-LA	621.4	507.9	413.7	428.4	428.4	438.6	472.5	466.1	1730.0	1409.0	1146.5	1187.3	1195.9	1216.2	1311.6	1294.1
2A-MS	581.6	517.3	395.1	367.7	367.7	361.3	496.4	324.5	1617.6	1437.4	1100.5	1023.3	1069.9	1004.9	1386.9	898.6
2A-TX	521.2	451.6	395.7	359.6	359.6	253.5	235.1	190.8	1448.8	1252.4	1096.7	995.3	873.7	697.6	645.7	520.6
2A-SC	355.8	428.7	286.8	300.5	266.3	225.2	202.5	190.4	984.6	1188.8	791.7	829.5	732.6	616.3	551.5	517.5
2B-AZ	431.2	413.5	329.1	319.5	273.1	267.3	237.3	237.7	1125.0	1074.7	844.1	817.7	693.7	677.4	596.7	598.0
2B-CA	243.1	210.6	183.2	173.4	157.3	143.2	124.7	124.4	621.8	532.9	459.1	432.6	389.9	352.9	305.3	304.6
2B-TX	436.6	375.4	326.9	297.8	262.3	209.6	195.5	159.2	1160.7	988.5	852.1	773.7	677.8	533.6	497.2	399.4
3A-AL	496.4	537.9	510.7	508.3	497.5	472.7	415.7	387.8	1320.9	1431.4	1359.3	1352.5	1322.7	1255.6	1100.8	1023.8
3A-AR	552.6	578.2	541.4	504.9	508.6	493.1	461.7	467.4	1474.4	1545.3	1443.8	1343.6	1352.9	1310.4	1224.1	1239.6
3A-GA	376.8	478.1	373.7	363.8	334.3	353.1	256.4	231.7	1000.7	1274.3	988.8	961.4	878.7	929.1	662.9	596.0
3A-LA	539.9	442.2	363.2	374.9	377.7	383.6	411.7	406.5	1441.9	1172.2	957.0	988.2	995.8	1012.1	1088.3	1074.3
3A-MS	506.5	454.4	353.8	329.9	343.0	324.6	432.9	288.0	1350.7	1208.8	937.2	870.5	906.1	857.9	1152.0	749.8
3A-NC	472.7	508.0	475.2	457.6	426.6	310.0	230.9	192.4	1256.8	1352.7	1263.6	1215.3	1130.4	808.4	592.0	489.1
3A-OK	450.6	332.5	251.8	249.5	223.7	196.0	141.3	134.5	1198.5	876.0	654.6	647.5	576.8	501.6	352.0	333.3
3A-SC	320.2	380.9	260.1	270.6	240.5	205.5	185.4	174.9	842.7	1006.9	675.1	703.4	620.5	523.8	467.2	438.9
3A-TN	492.9	448.0	386.7	373.0	378.4	377.0	365.3	259.0	1310.7	1189.2	1020.0	981.5	995.6	992.3	960.5	672.5
3A-TX	457.4	396.9	350.0	319.6	283.3	230.3	214.8	177.3	1217.2	1049.6	921.7	838.5	739.5	593.9	551.8	449.1
3B-AZ	422.9	405.6	323.8	314.7	269.1	263.5	234.1	235.2	1078.7	1030.3	812.8	788.4	669.1	653.6	576.6	579.6
3B-CA	239.5	207.8	181.0	171.6	155.9	142.3	124.2	123.9	598.2	513.7	443.1	418.4	377.8	342.6	296.8	296.0
3B-NM	755.3	793.8	729.4	663.2	434.3	393.9	222.6	195.8	1949.5	2047.7	1879.3	1710.2	1117.2	1013.1	563.7	495.6
3B-NV	336.7	344.7	290.3	289.4	242.3	247.7	214.4	199.7	848.2	871.2	728.1	725.6	600.7	614.9	526.0	489.8
3B-TX	428.4	368.8	321.7	293.0	258.5	207.1	193.1	157.7	1113.6	949.3	820.3	744.7	653.7	516.0	480.6	387.2
3B-UT	886.5	809.8	814.7	787.4	707.5	736.6	734.7	601.6	2278.0	2074.3	2086.6	2012.2	1794.7	1869.4	1872.7	1520.0
3C-CA	216.6	190.7	168.8	160.8	147.6	136.6	121.4	121.1	508.8	445.1	391.5	372.0	339.7	313.0	276.3	275.4
4A-AR	537.0	560.7	529.3	494.8	498.1	482.3	454.0	459.3	1360.3	1423.7	1341.3	1247.9	1256.2	1213.4	1138.9	1153.4
4A-DE	471.9	254.7	199.4	200.6	201.1	162.9	117.2	97.4	1188.2	618.5	475.5	478.6	478.3	380.7	255.4	203.9
4A-GA	374.6	469.7	374.4	364.1	338.2	355.1	267.4	243.8	938.2	1187.1	935.3	907.0	836.8	880.6	647.8	585.1
4A-IL	391.8	361.0	319.6	334.0	335.8	338.9	377.5	403.5	978.8	894.7	786.3	822.0	826.3	833.8	934.1	1002.6
4A-IN	954.3	872.5	852.4	816.7	783.7	766.5	632.3	539.7	2457.8	2237.2	2183.4	2088.7	2002.2	1956.9	1601.6	1359.0
4A-KS	609.3	474.9	417.5	442.4	412.8	371.8	277.4	281.0	1552.4	1193.2	1041.2	1105.2	1029.0	923.0	675.5	685.6
4A-KY	1089.6	993.4	980.8	723.0	704.7	650.9	477.5	389.5	2807.8	2554.0	2520.5	1837.2	1788.4	1647.4	1191.2	959.1

Region (CZ-State)	Primary school								Secondary school							
	2022	2026	2030	2034	2038	2042	2046	2050	2022	2026	2030	2034	2038	2042	2046	2050
4A-MD	269.8	267.9	232.6	243.8	301.3	248.7	164.9	197.6	654.5	655.5	563.9	592.1	743.9	602.2	380.1	466.1
4A-MO	956.5	960.4	762.4	755.5	741.7	714.6	619.9	553.7	2457.4	2466.1	1942.3	1924.0	1889.6	1817.5	1566.8	1391.8
4A-NC	464.7	496.5	466.9	450.2	421.4	315.7	243.3	207.1	1169.5	1252.7	1175.0	1130.0	1053.2	772.4	581.7	488.1
4A-NJ	353.1	320.8	285.6	277.4	311.3	322.2	347.5	344.0	872.9	789.3	697.8	675.5	764.6	793.7	860.3	851.1
4A-NY	285.6	200.7	165.7	153.5	171.9	161.9	159.6	156.5	699.9	475.0	383.0	350.7	398.5	371.6	365.1	356.0
4A-OH	733.1	752.7	716.1	640.8	630.5	569.6	517.0	411.2	1871.9	1922.2	1824.0	1626.5	1599.7	1439.8	1301.1	1021.0
4A-PA	488.1	466.8	463.9	505.0	512.5	471.0	433.7	412.0	1231.4	1173.5	1165.3	1272.7	1291.4	1182.5	1084.6	1027.8
4A-TN	483.1	440.2	383.9	371.4	377.0	376.1	366.0	267.1	1169.5	1252.7	1175.0	1130.0	1053.2	772.4	581.7	488.1
4A-VA	400.9	280.0	258.8	223.9	212.1	178.1	67.7	67.4	1000.7	682.5	626.6	535.6	504.8	414.7	122.5	121.7
4A-WV	662.5	744.5	706.1	574.1	471.7	358.6	289.6	307.1	1706.7	1918.2	1810.8	1474.1	1203.9	908.4	715.1	756.4
4B-AZ	412.7	397.0	321.1	312.8	269.8	264.6	237.0	237.7	1095.9	1052.2	848.1	824.6	708.8	693.8	619.3	621.5
4B-CA	239.1	209.7	184.8	175.9	160.9	147.7	130.1	129.8	624.2	544.5	477.3	453.1	412.6	376.1	328.7	328.0
4B-CO	646.1	621.0	536.1	503.2	479.3	396.9	308.5	274.4	1731.2	1659.8	1432.1	1342.2	1278.6	1053.1	816.6	725.6
4B-NM	726.9	764.3	704.0	640.9	423.4	384.8	222.6	197.0	1949.5	2046.8	1885.7	1716.6	1131.3	1027.5	587.4	518.8
4B-OK	408.3	301.4	228.1	225.9	203.1	178.1	129.5	123.9	1097.2	807.6	604.8	598.2	535.0	467.5	334.9	319.3
4B-TX	413.7	359.4	316.6	289.7	257.3	209.6	196.0	162.5	1110.1	958.4	841.7	768.2	680.5	550.3	513.6	421.6
4C-CA	244.4	218.8	197.0	189.0	176.0	164.8	149.4	149.2	553.4	490.7	437.4	417.7	385.9	358.2	321.0	320.4
4C-OR	188.0	153.9	144.0	140.5	125.4	134.9	133.1	115.8	415.9	333.0	309.1	300.6	263.3	286.5	282.2	239.8
4C-WA	107.4	93.2	90.4	91.2	87.5	91.4	95.0	83.6	219.1	184.6	177.9	179.8	170.8	180.3	189.2	161.5
5A-CT	299.4	275.2	256.0	249.3	281.2	290.0	374.1	332.5	725.8	665.6	616.1	599.8	680.9	702.3	915.9	809.0
5A-IA	642.0	627.9	606.9	564.0	448.5	407.0	314.8	268.0	1608.3	1568.3	1513.2	1399.9	1106.8	998.5	764.8	646.0
5A-IL	389.1	360.5	321.7	335.2	336.7	339.7	376.2	400.1	959.7	883.3	783.5	815.7	819.5	826.6	918.6	980.4
5A-IN	915.0	839.0	819.8	786.3	755.9	739.6	613.8	527.0	2310.4	2110.1	2058.9	1971.7	1894.6	1852.5	1525.8	1304.0
5A-KS	591.8	464.4	411.3	435.2	406.6	368.2	280.3	283.6	1481.1	1146.9	1009.6	1069.8	996.9	901.3	676.2	685.3
5A-MA	326.2	246.2	214.3	207.6	201.4	201.0	177.8	166.4	795.7	594.2	513.8	496.7	479.2	477.6	416.4	386.9
5A-MD	274.9	271.2	237.9	248.6	301.6	253.6	176.6	207.1	662.5	658.7	573.8	600.9	736.9	610.2	411.4	489.7
5A-MI	664.6	583.1	435.4	417.7	400.5	383.6	346.5	271.4	1663.8	1451.3	1067.3	1022.0	978.4	935.1	840.5	650.7
5A-MO	916.8	920.5	735.7	729.8	714.9	690.8	601.1	539.4	2308.0	2315.4	1837.3	1822.1	1784.8	1722.9	1490.1	1329.5
5A-NC	456.8	486.3	458.5	443.2	416.0	317.8	250.2	216.2	1132.2	1207.1	1135.5	1095.6	1024.3	769.6	595.5	509.9
5A-NE	469.2	464.9	400.8	465.8	395.0	297.4	250.6	205.0	1173.7	1159.5	988.0	1152.5	974.4	723.8	604.5	485.8
5A-NH	121.8	106.5	114.4	123.0	101.0	106.8	92.3	90.2	274.0	233.2	254.2	276.4	218.4	232.7	194.6	188.6
5A-NJ	354.2	323.5	290.4	283.0	314.9	324.6	348.2	345.1	865.7	788.2	704.1	684.6	766.8	792.1	852.8	844.8
5A-NY	289.6	210.9	177.9	166.7	184.2	174.9	172.8	170.0	704.0	500.9	416.1	387.4	432.0	407.1	401.5	393.0
5A-OH	709.4	727.8	693.6	622.8	612.8	556.7	507.1	408.1	1777.9	1823.5	1733.7	1552.3	1527.0	1383.4	1255.4	998.6
5A-PA	479.5	459.7	457.5	495.8	503.1	464.2	429.5	409.1	1191.2	1138.2	1132.3	1229.7	1247.7	1147.9	1059.2	1007.1
5A-RI	372.3	227.5	193.0	201.7	187.9	184.4	172.9	162.0	912.9	545.4	456.9	480.3	444.6	433.7	404.1	375.4
5A-SD	243.2	280.9	239.5	276.8	180.4	193.8	175.4	91.9	584.9	679.5	576.3	671.7	421.9	456.0	410.2	192.6
5A-WV	636.6	715.9	678.9	550.5	455.5	349.0	289.4	308.5	1610.6	1812.5	1709.9	1389.1	1142.9	871.8	706.8	752.8

Region (CZ-State)	Primary school								Secondary school							
	2022	2026	2030	2034	2038	2042	2046	2050	2022	2026	2030	2034	2038	2042	2046	2050
5B-AZ	411.3	396.6	323.6	315.8	275.4	270.2	243.4	244.2	1082.1	1041.3	842.6	821.3	712.0	697.4	624.7	627.2
5B-CA	246.1	217.9	194.2	185.6	171.5	159.3	142.8	142.5	633.4	556.6	492.4	469.2	431.0	397.6	353.3	352.6
5B-CO	633.9	609.7	528.6	498.2	475.6	396.3	312.4	279.5	1689.9	1620.4	1401.6	1318.2	1257.8	1039.8	816.4	728.7
5B-ID	123.1	116.2	101.5	149.0	151.8	161.2	193.0	180.6	301.9	283.3	243.7	371.3	376.5	401.6	487.2	454.3
5B-NM	709.7	746.7	689.7	629.1	422.9	386.7	231.6	206.7	1893.7	1990.8	1836.6	1673.8	1119.7	1022.9	601.8	534.9
5B-NV	333.8	340.9	292.6	291.9	250.2	254.9	225.1	211.5	870.8	890.5	759.8	757.9	644.7	657.1	575.3	539.4
5B-OR	187.0	148.7	137.5	133.2	117.3	127.4	125.4	107.1	475.5	371.7	341.2	329.2	286.1	313.5	308.2	258.3
5B-UT	830.6	763.0	768.4	744.8	674.8	700.7	699.3	578.8	2212.3	2026.9	2041.1	1975.1	1781.8	1851.6	1852.0	1523.1
5B-WA	99.2	83.8	80.8	81.3	77.6	81.6	85.4	73.5	238.0	196.8	188.7	190.2	180.2	191.0	201.1	169.4
5B-WY	833.6	893.0	830.0	701.7	651.3	556.9	508.6	342.8	2231.3	2390.1	2221.0	1875.7	1739.5	1485.7	1356.3	908.0
6A-IA	679.1	664.8	642.3	596.3	478.6	434.4	340.3	292.1	1722.7	1681.3	1620.9	1496.5	1194.2	1075.5	834.4	710.5
6A-ME	227.5	183.6	183.1	195.4	205.2	240.4	221.8	192.7	543.3	431.8	430.0	461.3	486.5	578.0	528.6	452.2
6A-MI	700.5	615.7	462.9	444.8	426.9	409.2	371.8	295.2	1772.7	1548.6	1144.2	1097.9	1051.9	1005.2	909.2	713.6
6A-MN	443.6	402.8	331.3	268.8	270.6	258.3	212.7	158.6	1105.6	999.5	809.7	646.8	651.5	619.1	502.7	362.1
6A-ND	608.0	659.3	606.4	628.7	533.5	470.7	369.8	273.7	1540.5	1669.5	1530.7	1586.3	1338.0	1173.4	912.2	664.7
6A-NH	141.0	125.1	133.0	141.3	119.6	125.3	110.7	108.4	321.4	278.1	299.4	320.9	262.7	277.3	238.0	231.5
6A-NY	313.3	232.5	198.7	187.3	205.0	195.4	193.2	190.2	768.1	556.7	468.5	439.2	484.4	458.4	452.5	443.2
6A-PA	509.4	488.7	486.4	525.8	533.5	493.3	457.4	436.4	1278.3	1221.8	1215.5	1317.1	1336.2	1231.9	1138.7	1084.4
6A-SD	266.3	304.3	263.1	299.8	203.1	214.5	197.6	110.6	646.7	743.9	640.4	732.9	481.1	509.7	467.6	237.1
6A-VT	102.9	102.9	102.9	102.9	168.6	189.5	181.4	177.2	216.7	216.7	216.7	216.7	387.1	441.0	421.0	409.9
6A-WI	755.0	782.4	741.8	652.0	623.0	571.6	508.6	464.9	1913.9	1982.6	1871.1	1630.2	1556.2	1421.3	1261.1	1151.1
6B-CA	271.8	245.6	223.2	215.0	201.6	189.9	174.0	173.8	657.3	587.5	528.1	506.4	470.9	439.6	397.8	397.5
6B-CO	639.4	617.6	541.2	513.0	491.7	417.2	336.5	305.6	1638.0	1576.4	1374.2	1298.7	1242.8	1042.7	832.3	752.2
6B-ID	153.0	146.8	133.1	179.7	183.5	192.7	223.8	212.3	344.3	328.0	292.2	415.2	423.1	447.2	529.7	499.9
6B-MT	280.3	530.5	513.2	495.1	448.1	359.0	334.3	282.7	680.8	1343.9	1299.6	1252.2	1128.5	894.6	831.5	695.1
6B-UT	827.9	763.3	770.6	750.1	685.8	710.0	706.5	593.6	2127.4	1953.3	1971.8	1916.4	1741.8	1804.9	1800.4	1498.5
6B-WA	130.7	116.0	113.2	113.9	110.1	114.0	117.7	106.1	286.0	247.6	240.0	241.9	232.1	242.5	252.2	221.7
6B-WY	832.0	888.2	829.9	708.1	660.7	570.5	524.2	365.6	2152.3	2298.7	2146.3	1825.8	1700.8	1463.1	1341.8	921.6
7-CO	690.0	667.2	590.2	560.6	539.3	463.7	381.1	349.2	1682.6	1620.0	1422.7	1345.8	1291.5	1095.2	885.6	805.1
7-ME	247.9	206.9	206.5	217.7	227.4	260.2	243.2	216.3	548.4	445.1	443.6	471.8	496.3	580.5	536.2	466.3
7-MI	688.7	611.1	471.3	454.3	437.3	421.0	385.6	312.9	1680.7	1477.7	1112.0	1068.6	1025.7	982.8	893.4	709.7
7-MN	449.8	411.9	346.0	288.3	290.0	278.6	235.9	184.2	1068.6	970.1	796.7	648.6	653.2	623.2	515.9	382.9
7-ND	601.7	650.0	601.7	622.8	535.5	477.7	383.2	292.0	1464.9	1585.2	1459.2	1511.2	1286.5	1137.8	895.7	662.9
7-WI	740.4	766.5	731.2	650.1	622.9	574.7	515.4	473.6	1813.4	1877.6	1780.6	1565.1	1496.2	1372.1	1223.2	1118.5
7-WY	883.6	941.3	881.2	756.5	707.8	615.3	567.6	407.0	2181.3	2327.8	2174.7	1855.7	1731.4	1495.0	1374.0	961.6

Reference

[1] FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies - The White House, (n.d.). https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/.

[2] United States Mid-Century Strategy FOR DEEP DECARBONIZATION, (2016).

[3] Solar Schools Campaign Toolkit Download - Generation180, (n.d.). https://generation180.org/solar-schools-campaign-toolkit-download/.

[4] Overview, How Old are America's Public Schools?, (n.d.). https://nces.ed.gov/surveys/frss/publications/1999048/.

[5] N. Moazzen, T. Ashrafian, Z. Yilmaz, M.E. Karagüler, A multi-criteria approach to affordable energy-efficient retrofit of primary school buildings, Appl. Energy. 268 (2020) 115046. https://doi.org/10.1016/J.APENERGY.2020.115046.

[6] F. Hu, X. Zheng, Carbon Emission of Energy Efficient Residential Building, Procedia Eng. 121 (2015) 1096–1102. https://doi.org/10.1016/j.proeng.2015.09.111.

[7] J. He, Research on Deepening Design and Construction of Cross-Sea Tunnel Based on the Principle of Prefabricated Building, IOP Conf. Ser. Earth Environ. Sci. 598 (2020). https://doi.org/10.1088/1755-1315/598/1/012016.

[8] L. Dong, Y. Wang, H.X. Li, B. Jiang, M. Al-Hussein, Carbon reduction measures-based LCA of prefabricated temporary housing with renewable energy systems, Sustain. 10 (2018). https://doi.org/10.3390/su10030718.

[9] Energy Information Administration (EIA)- Commercial Buildings Energy Consumption Survey (CBECS), (n.d.). https://www.eia.gov/consumption/commercial/.

[10] Education for sustainable development good practices in early childhood, (2012). https://unesdoc.unesco.org/ark:/48223/pf0000217413

[11] Y. Lou, Y. Yang, Y. Ye, W. Zuo, J. Wang, The effect of building retrofit measures on CO2 emission reduction – A case study with U.S. medium office buildings, Energy Build. 253 (2021). https://doi.org/10.1016/J.ENBUILD.2021.111514.

[12] Y. Lou, Y. Ye, Y. Yang, W. Zuo, Long-term carbon emission reduction potential of building retrofits with dynamically changing electricity emission factors, Build. Environ. 210 (2022). https://doi.org/10.1016/J.BUILDENV.2021.108683.

[13] H. Sozer, Improving energy efficiency through the design of the building envelope, Build. Environ. 45 (2010) 2581–2593. https://doi.org/10.1016/J.BUILDENV.2010.05.004.

[14] S.B. Sadineni, S. Madala, R.F. Boehm, Passive building energy savings: A review of building envelope components, Renew. Sustain. Energy Rev. 15 (2011) 3617–3631. https://doi.org/10.1016/J.RSER.2011.07.014.

[15] T.M.I. Mahlia, A. Iqbal, Cost benefits analysis and emission reductions of optimum thickness and air gaps for selected insulation materials for building walls in Maldives, Energy. 35 (2010) 2242–2250. https://doi.org/10.1016/J.ENERGY.2010.02.011.

[16] P. Jie, F. Zhang, Z. Fang, H. Wang, Y. Zhao, Optimizing the insulation thickness of walls and roofs of existing buildings based on primary energy consumption, global cost and pollutant emissions, Energy. 159 (2018) 1132–1147. https://doi.org/10.1016/J.ENERGY.2018.06.179.

[17] G. Doiphode, H. Najafi, M. Migliori, Energy Efficiency Improvement in K-12 Schools: A

Case Study in Florida, ASME J. Eng. Sustain. Build. Cities. 2 (2021). https://doi.org/10.1115/1.4048894.
[18] W. Li, C. Koo, T. Hong, J. Oh, S.H. Cha, S. Wang, A novel operation approach for the energy efficiency improvement of the HVAC system in office spaces through real-time big data analytics, Renew. Sustain. Energy Rev. 127 (2020). https://doi.org/10.1016/J.RSER.2020.109885.
[19] Analysis of Whole-Building HVAC System Energy Efficiency: EBSCOhost, (n.d.). https://web.s.ebscohost.com/ehost/detail/detail?vid=0&sid=a093829d-960e-44cd-82a5-f1774392f20e%40redis&bdata=JkF1dGhUeXBlPWlwJnNpdGU9ZWhvc3QtbGl2ZSZzY29wZT1zaXRl#AN=129383764&db=a2h.
[20] M.C. Dubois, Å. Blomsterberg, Energy saving potential and strategies for electric lighting in future north european, low energy office buildings: A literature review, Energy Build. 43 (2011) 2572–2582. https://doi.org/10.1016/J.ENBUILD.2011.07.001.
[21] G. Lowry, Energy saving claims for lighting controls in commercial buildings, Energy Build. 133 (2016) 489–497. https://doi.org/10.1016/J.ENBUILD.2016.10.003.
[22] Y. Lou, Y. Yang, Y. Ye, C. He, W. Zuo, The economic impacts of carbon emission trading scheme on building retrofits: A case study with U.S. medium office buildings, Build. Environ. 221 (2022) 109311. https://doi.org/10.1016/J.BUILDENV.2022.109311.
[23] A.R. Gamarra, I.R. Istrate, I. Herrera, C. Lago, J. Lizana, Y. Lechón, Energy and water consumption and carbon footprint of school buildings in hot climate conditions. Results from life cycle assessment, J. Clean. Prod. 195 (2018) 1326–1337. https://doi.org/10.1016/J.JCLEPRO.2018.05.153.
[24] Z. Liu, B. Cai, PA P E R J U N E 2 0 1 8 High-resolution Carbon Emissions Data for Chinese Cities, (2018). www.belfercenter.org/ENRP.
[25] Q. Liu, J. Song, T. Dai, A. Shi, J. Xu, E. Wang, Spatio-temporal dynamic evolution of carbon emission intensity and the effectiveness of carbon emission reduction at county level based on nighttime light data, J. Clean. Prod. 362 (2022) 132301. https://doi.org/10.1016/J.JCLEPRO.2022.132301.
[26] H. Zhang, J. Peng, D. Yu, R. Wang, T. Panagopoulos, Carbon Emission Governance Zones at the County Level to Promote Sustainable Development, L. 2021, Vol. 10, Page 197. 10 (2021) 197. https://doi.org/10.3390/LAND10020197.
[27] Z. Long, Z. Zhang, S. Liang, X. Chen, B. Ding, B. Wang, Y. Chen, Y. Sun, S. Li, T. Yang, Spatially explicit carbon emissions at the county scale, Resour. Conserv. Recycl. 173 (2021) 105706. https://doi.org/10.1016/J.RESCONREC.2021.105706.
[28] H. Zhang, J. Peng, D. Yu, R. Wang, T. Panagopoulos, Carbon Emission Governance Zones at the County Level to Promote Sustainable Development, L. 2021, Vol. 10, Page 197. 10 (2021) 197. https://doi.org/10.3390/LAND10020197.
[29] A. Cheshmehzangi, Low carbon transition at the township level: feasibility study of environmental pollutants and sustainable energy planning, Https://Doi.Org/10.1080/14786451.2020.1860042. 40 (2020) 670–696. https://doi.org/10.1080/14786451.2020.1860042.
[30] Y. Dong, Y. Zhao, J. Zhang, P. Liu, Development of a framework of carbon accounting and management on the township level in China, J. Environ. Manage. 318 (2022) 115609. https://doi.org/10.1016/J.JENVMAN.2022.115609.
[31] Climate Zones | Department of Energy, (n.d.). https://www.energy.gov/eere/buildings/climate-zones.

[32] Use of energy in commercial buildings - U.S. Energy Information Administration (EIA), (n.d.). https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php.
[33] C. W. Gagnon, Pieter, Frazier, Will, Hale, Elaine, Cambium data for 2020 standard scenarios, Natl. Renew. Lab. (2020). https://scenarioviewer.nrel.gov/.
[34] P. Gagnon, W. Frazier, W. Cole, E. Hale, Cambium Documentation: Version 2021, (2021). https://www.nrel.gov/docs/fy22osti/81611.pdf.
[35] U.S. Energy Information Administration - EIA - Independent Statistics and Analysis, (n.d.). https://www.eia.gov/environment/emissions/co2_vol_mass.php.
[36] Prototype Building Models | Building Energy Codes Program, (n.d.). https://www.energycodes.gov/prototype-building-models.
[37] R. Jarnagin, G. Bandyopadhyay, Weighting Factors for the Commercial Building Prototypes Used in the Development of ANSI / ASHRAE / IENSA Standard 90 . 1-, (2010).
[38] A./ Ashrae, / Iesna Addenda, ANSI/ASHRAE/IESNA Addenda a, b, c, g, h, i, j, k, l, m, n, p, q, s, t, u, w, y, ad, and aw to ANSI/ASHRAE/IESNA Standard 90.1-2007, (2009).
[39] M. Tyler, D. Winiarski, M. Rosenberg, B. Liu, Impacts of Model Building Energy Codes – Interim Update, (2021). https://www.ntis.gov/about.
[40] 2012 International Energy Conservation Code (IECC), (n.d.). https://codes.iccsafe.org/content/IECC2012.
[41] Y. Ye, K. Hinkelman, Y. Lou, W. Zuo, G. Wang, J. Zhang, Evaluating the energy impact potential of energy efficiency measures for retrofit applications: A case study with U.S. medium office buildings, Build. Simul. 14 (2021) 1377–1393. https://doi.org/10.1007/S12273-021-0765-Z.
[42] R.S. Srinivasan, J. Lakshmanan, E. Santosa, D. Srivastav, Plug-load densities for energy analysis: K-12 schools, Energy Build. 43 (2011) 3289–3294. https://doi.org/10.1016/J.ENBUILD.2011.08.030.
[43] B. Griffith, N. Long, P. Torcellini, R. Judkoff, D. Crawley, J. Ryan, Assessment of the Technical Potential for Achieving Net Zero-Energy Buildings in the Commercial Sector, (2007). http://www.osti.gov/bridge.
[44] H.M. Cho, S. Yang, S. Wi, S.J. Chang, S. Kim, Hygrothermal and energy retrofit planning of masonry façade historic building used as museum and office: A cultural properties case study, Energy. 201 (2020). https://doi.org/10.1016/J.ENERGY.2020.117607.
[45] M. Rabani, H. Bayera Madessa, O. Mohseni, N. Nord, Minimizing delivered energy and life cycle cost using Graphical script: An office building retrofitting case, Appl. Energy. 268 (2020). https://doi.org/10.1016/J.APENERGY.2020.114929.
[46] B.M. Santamaria, F. Del Ama Gonzalo, D. Pinette, R.A. Gonzalez-Lezcano, B.L. Aguirregabiria, J.A.H. Ramos, Application and Validation of a Dynamic Energy Simulation Tool: A Case Study with Water Flow Glazing Envelope, Energies 2020, Vol. 13, Page 3203. 13 (2020) 3203. https://doi.org/10.3390/EN13123203.
[47] ASHRAE, Advanced Energy Design Guide for K-12 School Buildings, 2011.
[48] Total Energy Annual Data - U.S. Energy Information Administration (EIA), (n.d.). https://www.eia.gov/totalenergy/data/annual/.
[49] Winter Heating Fuels - Energy Information Administration, (n.d.). https://www.eia.gov/special/heatingfuels/#/US:propane:week.
[50] Clean Energy | Department of Energy, (n.d.). https://www.energy.gov/clean-energy.
[51] F. Dehdar, J.A. Fuinhas, N. Karimi Alavijeh, N. Nazeer, S. Zangoei, Investigating the determinants of carbon emissions in the USA: a state-level analysis, Environ. Sci. Pollut.

Res. 1 (2022) 1–12. https://doi.org/10.1007/S11356-022-23831-X/TABLES/7.

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