Regional carbon emission reduction prediction via retrofits of commercial buildings with a case study of US school buildings in hot climates

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Regional carbon emission reduction prediction via retrofits of commercial buildings with a case study of US school buildings in hot climates

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Abstract

Retrofitting commercial buildings has great potential to reduce carbon emissions as demonstrated by previous studies in some specific cities, but their regional carbon emission reduction potential is still unknown. Thus, we develop a method to predict the long-term regional carbon emission reduction potential by retrofitting commercial buildings. School buildings in hot climate zones in the continental U.S. are selected as an example. The results show that the aggregated carbon emission reduction potential of school buildings in that region reduces from 3.33 to 2.01 megatons from 2024 to 2050 due to the increased penetration of renewable energy.

Highlights

- A novel method is developed for large-scale regional carbon emission reduction assessment
- The regional aggregated carbon emission reduction potential of building retrofit is estimated by utilizing weighting factors
- The dynamic long-run marginal emission rate is adopted for long-term carbon emissions prediction
- School buildings in hot climates are chosen for the case study to evaluate long-term carbon emission reduction potential

Introduction

The United States (U.S.), as the second-largest contributor to carbon emissions, aims to mitigate climate change caused by greenhouse gas (GHG) with an outlined pathway to reduce carbon emissions 80 % by 2050 (*United States Mid-Century Strategy FOR DEEP DECARBONIZATION*, 2016). The U.S. buildings sector accounts for 36% of energy-related carbon emissions, which has a great potential to reduce carbon emissions (*Energy Information Administration (EIA)- Commercial Buildings Energy Consumption Survey (CBECS)*, n.d.). Currently, there are plenty of buildings that are underperforming with low energy efficiency and high carbon emissions and will still be in function until 2050 (Ghazi Wakili et al., 2014; Ürge-Vorsatz et al., 2011).

The previous research proved that building retrofits have great potential to improve building performance by reducing energy consumption and carbon emission in specific areas (Lou et al., 2021, 2022; Sadineni et al., 2011; Sozer, 2010). To further contribute to the low-carbon development goals, many researchers indicate that understanding carbon emission reduction on the regional level is critical and should be highlighted in carbon management (Cheshmehzangi, 2020; Y. Dong et al., 2022; Long et al., 2021; Zhang et al., 2021). Moreover, Yang et al. (2023) investigated national carbon intensity reduction of retrofitting school buildings, and the results indicated that the carbon intensity reduction potential is varied by different regions. Carbon intensity means the kilograms of carbon dioxide equivalent emitted per square meter and is one of the emerging metrics to measure the carbon emissions of buildings (L. Dong et al., 2018; Hu & Zheng, 2015). To some degree, the carbon intensity can reflect the potential of building retrofits in a specific region. However, when considering the diversity of population density and construction area, the level of carbon intensity cannot fully examine the carbon emission reduction potential. For example, even if carbon intensity in a specific region is relatively low, the large construction area can still be the reason for excessive carbon emission. Therefore, the aggregated carbon emission reduction potential on a region-by-region basis enables a more reasonable metric to evaluate the carbon reduction potential of building retrofits.

However, current research on carbon emission reduction of building retrofits cannot fill the research gap in the evaluation of regional aggregated carbon emission reduction because the available energy resources, climate features, and building floor space in different locations vary significantly. For example, the regions in Texas have six types of climate zones 1A (very hot humid), 2A (hot humid), 2B (hot dry), 3A (warm humid), 3B (warm dry), and 4B (mixed dry). In regional carbon emission reduction of building retrofit, both state and climate information should be included in the estimation. Moreover, considering the operational and structural implications of changes in electricity demand, a new metric to evaluate long-term carbon emission is needed to reflect the scaled-up end-use load from the base run. The the long-term regional level evaluation can deliver a regional aggregated carbon emission reduction to policymakers so that they make an informed decision for building retrofit policy.

This research aims to investigate regional aggregated carbon reduction potential, which has not been fully investigated yet. Therefore, a method is developed to predict the long-term regional carbon emission reduction potential by retrofitting aggregated commercial buildings based on the result of building energy modeling. Then, the long-run marginal emission rate of electricity is used to explore the carbon reduction potential of commercial buildings, which considers the long-term change in electrical demand and incorporates both the operational and structural consequences of the demand change. Finally, to calculate the aggregated carbon emission reduction of commercial buildings, we adopted the weighting factors of floor area calculated from the existing construction database.

School buildings in hot climate zones in the continental U.S. are selected as an example to illustrate the method. Since school facilities annually emit about 72 million metric tons of carbon dioxide, which is equivalent to the emissions from about 8.6 million homes (*Solar Schools Campaign Toolkit Download - Generation180*, n.d.). As one of the significant infrastructures in the United States (U.S.), school buildings have a great potential to reduce carbon emissions. Based on the existing report, more than 30% of school buildings are underperformance with low energy efficiency and high carbon emission (*Overview, How Old Are America's Public Schools?*, n.d.). Moreover, the Commercial Buildings Energy Consumption Survey conducted by the U.S. Energy Information Administration (*U.S. Energy Information Administration - EIA - Independent Statistics and Analysis*, n.d.) indicates that schools annually spend around $8 billion on utility bills which forces public administrations to make strategic decisions concerning the refurbishment of the school building stock. It is also worth to be mentioned that, as the buildings with education function, reducing carbon emission via school buildings is a good opportunity to promote sustainability for students and their family members. (*Education for Sustainable Development Good Practices in Early Childhood*, 2012)

The rest of this paper is organized as follows: Section 2 introduces the methodology of predicting the carbon emission reduction potential of aggregated commercial buildings; Section 3 describes the application of this method in school buildings located in hot climate zones from 2024 to 2050 including information on selected locations, baseline school building energy models and retrofit measures, and weighting factors of floor area between primary and secondary school buildings; Section 4 presents and discussed the results of carbon emission reduction of school buildings from 2024 to 2050; Finally, Section 5 concludes the research work.

Method

Energy Saving

A building can have different sources of energy. Therefore, the hourly energy reduction due to retrofits for a building b_{z_n} belonging to the specific building type z_n in the climate zone i can be obtained using the following formula:

$$\Delta X_{i,t,b_{z_n}} = X\_base_{i,t,b_{z_n}} - X\_\mathrm{retr}_{i,t,b_{z_n}}, \qquad (1)$$

where X represents the energy source used in the commercial building, which can be electricity, natural gas, fuel oil, etc. The X_base represents energy source consumption of the building before retrofits; the X_retr represents energy source consumption of the building after retrofits. The building retrofit measures are considered to improve building performance and reduce carbon emission, which could be increasing the insulation of building envelops, improving the efficiency of HVAC system, etc.

Carbon Emission Reduction

In the previous equations, we acquire the hourly energy reduction of electricity and natural gas for a retrofitted building. Based on previous research (Lou et al., 2021, 2022; Yang et al., 2023), the carbon emission reduction due to building retrofit can be calculated by multiplying the energy savings with the energy emission factors in corresponding time and locations. Therefore, the annual carbon emission reduction due to retrofits for a building b_{z_n} belonging to the specific building type z_n in climate zone i and state s can be expressed as the following equation:

$$\mathrm{C}_{\mathrm{i,s,y,b_{z_n}}} = \sum_{\mathrm{t=1}}^{\mathrm{T}} \sum_{\mathrm{k=1}}^{\mathrm{K}} (\Delta \mathrm{X}_{\mathrm{k,i,t,b_{z_n}}} \times \mathrm{Fx}_{\mathrm{k,s,t,y}}) \qquad (2)$$

$$Fx_{k,s,t,y} = \mathrm{C} \text{ or } Fx_{k,s,t,y} = f(t) \qquad (3)$$

where the C represents carbon emission reduction; the y represents the specific year that is investigated in the research; the t represents time unit (e.g. hour, minute) which can also represent the time unit of energy source change; the T is the total period for the carbon reduction evaluation; the k represents a type of energy source used in the commercial building; the K is the total types of energy source used in the commercial building; the Fx represents the emission factor of energy source, which can be dynamically changing (Gagnon et al., 2023) or constant depending on different types of energy source. For example, according to the open-source software Cambium, the long-run carbon emission rate is estimated with a scalar increase in end-use electricity demand compared with base run, then when considering the long-term change in electrical demand and incorporating both the operational and structural consequences of the change, the dynamically changing long-run marginal emission rate can be adopted to estimate the carbon emission generated by electricity. (Gagnon et al., 2023)

After calculating the annual carbon emission reduction of the building after retrofits belonging to the specific building type. The regional carbon emission reduction of building retrofits for aggregated commercial buildings in the climate zone i and state s

$$C_{i,s,y,\mathrm{z_1+\cdots+z_n}} = \sum_n^N A_{z_n} \times \sum_{n=1}^N (w_{\mathrm{z_n,i},s} \times \frac{C_{i,s,y,b_{\mathrm{z_n}}}}{A_{b_{z_n}}}), \qquad (4)$$

$$w_{\mathrm{z_n,i},s} = \frac{A_{\mathrm{z_n,i},s}}{\sum_n^N A_{\mathrm{z_n,i},s}}, \qquad (5)$$

where, $z_1, z_2, \cdots, z_n$ represent the different commercial building types; the y represents the specific year investigated in the research; the A_{z_n} is the total floor area of commercial building type z_n in the U.S. and can be acquired via the existing database such as CBECS data

Table 1: Model Input Value of Baseline Model and Retrofitted Model

Building Retrofit Measure	Model Input	Building Types	1A		2A		2B	
			Base[1]	Retr[2]	Base[1]	Retr[2]	Base[1]	Retr[2]
Add wall insulation	Wall insulation R-value (m2-K/W)	Primary & Secondary School	1.04	1.04	1.04	1.34	1.04	1.34
Add roof insulation	Roof insulation R-value (m2-K/W)	Primary & Secondary School	2.60	3.52	3.47	4.41	3.47	4.41
Replace windows	Window U-factor (W/m2-K)	Primary & Secondary School	6.82	3.18	4.09	2.56	4.09	2.56
	Window SHGC		0.25	0.25	0.25	0.25	0.25	0.25
Improve lighting efficiency	Lighting power density (W/m2)	Primary School	12.80	7.53	12.80	7.53	12.80	7.53
		Secondary School	12.16		12.16		12.16	
Improve equipment efficiency (excluding kitchen)	Plug load density (W/m2)	Primary School	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
Improve cooling coil efficiency	Nominal coefficient of performance	Primary & Secondary School	3.23	3.37	3.23	3.37	3.23	3.37
Improve heating efficiency	Burner efficiency	Primary & Secondary School	0.80	0.90	0.80	0.90	0.80	0.90
Improve service hot water system efficiency	Heater thermal efficiency	Primary & Secondary School	0.81	0.95	0.81	0.95	0.81	0.95

[1] Base: Baseline model (Source: ASHRAE Standard 90.1–2007 (Ashrae & Iesna Addenda, 2009))
[2] Retr: Retrofit model (Source: AEDG K-12 school buildings 50% Energy Savings (ASHRAE, 2011))

(*Energy Information Administration (EIA)- Commercial Buildings Energy Consumption Survey (CBECS)*, n.d.); $A_{b_{z_n}}$ represents the floor area of a commercial building b_{z_n}; $C_{i,s,y,b_{z_n}}$ can be acquired from equation (4); $w_{z_1,i,s}$ represents the weighting factor of floor area for a building type z_1 in state s and climate zone i. The weighting factor can be obtained from many databases including the construction information of commercial buildings that can be adopted to calculate the weighting factor by using equation (5). For example, the Pacific Northwest National Laboratory (PNNL) evaluated weighting factors w for the national commercial building construction of climate zones and states in the U.S. based on the Dodge Data & Analytics database. (Lei et al., 2003)

Design for Case Study

To implement the methodology detailed in the previous section, existing U.S. school buildings including primary and secondary school buildings in hot climate zones are selected for a case study. As mentioned before, school buildings have a great potential to reduce carbon emissions due to high carbon emission and poor building performance. Moreover, the high temperature in hot climates exacerbates the demand for cooling and leads to high carbon emission reduction potential for buildings in those areas. This section provides school buildings energy models including investigated locations, primary and secondary school building models, values for building retrofit measures, and the weighting value to calculate the regional aggregated carbon emission reduction.

Investigated location

According to IECC 2021 (*Digital Codes*, n.d.) hot climates in the U.S. include 1A (very hot humid), 2A (hot humid), and 2B (hot dry), which covers 9 states (Alabama, Arizona, California, Florida, Georgia, Louisiana, Mississippi, South Caroline, and Taxes) in the continental U.S. Climate 1A includes some locations in Hawaii, however, the carbon emission factors in Hawaii are not available according to the existing data of Cambium 2022 (Gagnon et al., 2023). Therefore, Hawaii is not investigated in this research. Considering the climate features and state, the hot climates in the U.S. can be divided into 12 regions, as shown in Figure 1.

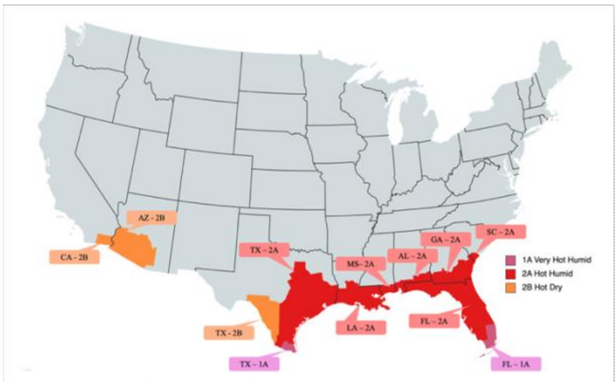

Figure 1: Locations investigated in case study

Building energy modeling

There are many buildings retrofit measures available for commercial buildings (Griffith et al., 2007; Moazzen et al., 2020; Santamaria et al., 2020; Srinivasan et al., 2011). In this study, the building type is identified with the building's function such as small office, primary school. Other building types can refer to the U.S. Department of Energy (U.S. DOE) prototype buildings (*Prototype Building Models | Building Energy Codes Program*, n.d.) K-12 school buildings including primary and secondary school buildings are selected to examine the impact of eight building retrofit measures on the carbon emission of

K-12 school buildings in hot climate zones. Table 1 shows these eight retrofit measures. We examined the emission reduction potential of the aggregated effect of these eight measures. One building retrofit model applying these eight measures is created. Thus, there are 12 building energy models (2 building type × 3 climate features × (1 baseline model + 1 retrofit model)) in this study. It is well noted that the 2012 Actual Meteorological Year (AMY) weather data is used for the building energy modeling. Since the carbon emission rate adopted in this study is from an open-source tool Cambium 2022 (Gagnon et al., 2023). 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 (Gagnon et al., 2023).

For the suggested model input values of retrofit models in three hot climate zones, the detailed upgrading strategies could be found in Advanced Energy Design Guide 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; 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; 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. (ASHRAE, 2011)

The model input values of baseline models are based on ASHRAE Standard 90.1-2007 (Ashrae & Iesna Addenda, 2009). 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. This study only considers electricity and natural gas for the energy consumption of buildings because these two are the most common energy sources used in commercial buildings in the U.S., which accounts for 93% (*Use of Energy in Commercial Buildings - U.S. Energy Information Administration (EIA)*, n.d.). Electricity is consumed for AC cooling and reheating, lighting, and plug loads, and natural gas is used for AC heating and service water heating.

Weighting factors for selected locations

According to the technical report of PNNL on the basis of the Dodge Data & Analytics database (Lei et al., 2003), the weighting factors of floorspace between primary and secondary schools are remapped based on the climate zone and state information, as shown in Table 2.

Table 2: Weighting factors of floorspace for school buildings in hot climate regions

Region (Climate Zones-State)	Primary school	Secondary school
1A - FL	0.17	0.83
1A - TX	0.31	0.69
2A - AL	0.20	0.80
2A - FL	0.46	0.54
2A - GA	0.35	0.65
2A - LA	0.46	0.54
2A - MS	0.41	0.59
2A - SC	0.13	0.87
2A - TX	0.27	0.73
2B - AZ	0.47	0.53
2B - CA	0.26	0.74
2B - TX	0.25	0.75

Results

Annual carbon emission in hot climate zones

Based on the method and study design, the annual carbon emission reduction potential from 2024 to 2050 can be predicted, as shown in Figure 2. On average, the annual carbon emission reduction potential is 2.1 megatons from 2024 to 2050. From a long-term perspective, the annual carbon emission reduction potential in the hot climate zones of the continental U.S. will decrease. In the year 2024, the annual carbon emission reduction potential is 3.33 megatons, and in the year 2050, it will be 2.01 megatons. However, the annual carbon emission reduction does not always decrease all the time. From the year 2030 to 2040, the carbon emission reduction potential will increase.

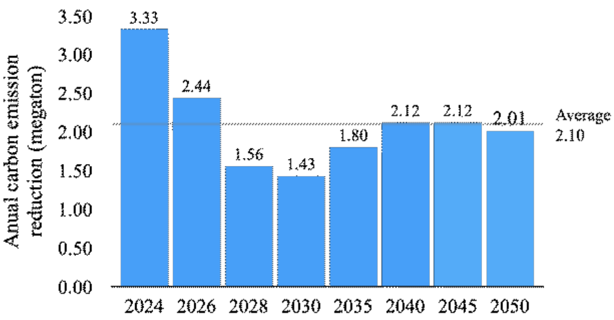

Figure 2: Annual carbon emission reduction of retrofitted buildings in hot climate zones

Annual carbon intensity changes in hot climate zones

This study also examines annual carbon reduction potential via carbon intensity reduction. The heatmap of carbon intensity change in 12 regions from 2024 to 2050 is created to further explore the carbon emission change on a region-by-region basis., as shown in Figure 3.

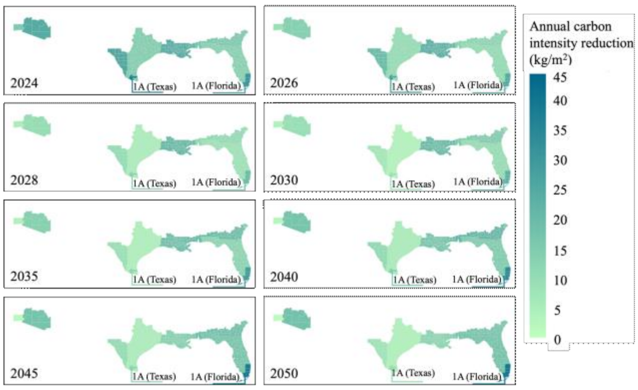

Figure 3: Annual carbon intensity reduction of retrofitted school buildings in hot climate zones

As shown in Figure 3, in general, the shading of color is gradually shallow compared to the year 2024 with the year 2050. Among the three hot climate zones, the climate 1A (very hot and humid) including Florida and Texas has the greatest carbon intensity reduction. Moreover, the region in Florida within climate zone 1A has the greatest carbon intensity reduction potential among the 12 regions investigated in this study. However, shading of region in Florida state with very hot and humid cliamte feature does not always become shallow. After 2023, the shading of the region becomes deep.

Discussion

Impact of location

According to Figure 3, the top three regions that have the highest carbon reduction potential almost reduce all year. Table 3 summarizes the top three regions which have the highest carbon reduction potential among 12 regions from 2024 to 2050. The region in Florida state with climate feature 1A (very hot and humid) has the highest annual carbon emission reduction potential after 2030. It is because climate zone 1A (very hot and humid) has a high demand for electricity and a high population which leads to higher carbon emissions compared with other regions and has a high potential to reduce carbon emissions. In the next subsection, we will further explore the reason based on electricity generation.

Table 3. 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)
2024	Texas - 1A, Florida - 1A, Texas – 2B
2026	Texas - 1A, Florida – 1A, Louisiana – 2A
2028	Louisiana – 2A, Missouri – 2A, Florida – 1A
2030	Florida – 1A, Missouri – 2A, Louisiana – 2A
2035	Florida – 1A, Georgia – 2A, Missouri – 2A
2040	Florida – 1A, Georgia – 2A, Albama-2A
2045	Florida – 1A, Georgia – 2A, Albama-2A
2050	Florida – 1A, Arizona – 2B, Florida - 2A

Impact of renewable energy generation

Based on the previous subsection, we find that the region in Florida within climate 1A has great potential to reduce carbon emissions from 2024 to 2050. Then, the region Florida-1A is selected to detailed examine the impact of renewable energy generation. From a long-term perspective, the penetration of renewable energy will increase. Consequently, the generation from renewable generators, including photovoltaics (PV), concentrating solar power (CSP) without storage and wind (Gagnon et al., 2023), will increase, as shown in Figure 4. However, the annual growth rate of renewable energy generation will decrease. From the year 2024 to the year 2050, in the beginning, the generation from renewable energy generation grows rapidly, then, the growth trend flatting, and in years 2045 and year 2050, the total generation from renewable energy generation is almost the same. Since the capacity of renewable energy will reach its "glass ceiling", the increasing rate of renewable energy generation will be lower than the total electric load. Therefore, the net electric load will increase, as shown in Figure 4. To meet the increasing load desire, the consumption of dirty energy will increase. As a result, the carbon emission reduction potential of building retrofit measures will increase. There are multiplied potential reasons for the increase in total electric loads, such as population growth, and construction increase.

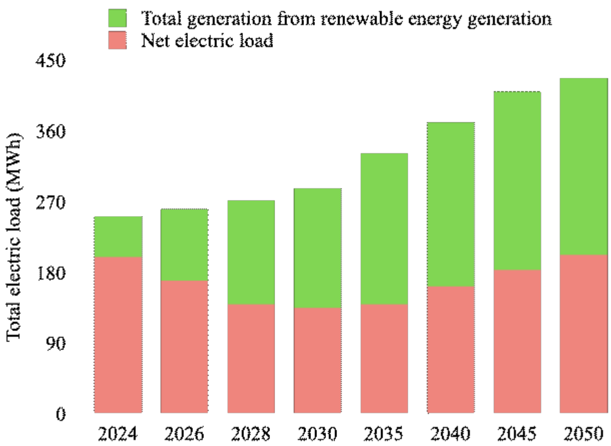

Figure 4: Total electric load in Florida from 2024 to 2050

Future work for large scale reginal carbon emission reduction

This study proposes a method to build a foundation for estimating the regional carbon reduction potential of aggregated commercial buildings. Then school buildings in hot climate zones of the U.S. are chosen as an example to apply the method. The results of the selected example indicate the feasibility of evaluating the aggregated carbon reduction potential of building retrofits on a region-by-region basis on a national or worldwide scale. In the future, more scenarios can be adopted to make the result more representative and enable geographical and social-economic diversity of large-scale evaluation. For example, the energy sources used in commercial buildings will be different in different regions. In this study, we only consider electricity and natural gas as energy sources for commercial buildings in hot climate zones. However, for some climate zones, such as cold climate zones, fuel oil is also the energy source for commercial buildings. Then equation $\Delta X_{i,t,b_{z_n}} = X\_base_{i,t,b_{z_n}} - X\_\mathrm{retr}_{i,t,b_{z_n}}$, () can be used for fuel oil to evaluate the regional carbon emission reduction.

Conclusion

This research develops a method to predict the regional aggregated carbon emission reduction potential of the retrofits for existing commercial buildings. The proposed prediction method on a region-by-region basis will reduce more uncertainties in carbon emission calculation caused by geographical and social-economic diversity by considering the various energy sources, climate features, and construction areas in different regions. Moreover, this research enables long-term carbon emission assessment powered by large-scale building energy modeling and simulation and the application on school buildings in hot climate zones in the U.S. improves the feasibility of evaluating the aggregated carbon reduction potential of building retrofits on a region-by-region basis on a national or worldwide scale. To represent all hot climates, the area is divided into 12 regions considering the climate features and state information. The aggregated carbon emission reduction potential of school buildings in the hot climate zones is reduced from 3.33 megatons to 2.01 megatons from 2024 to 2050. The carbon intensity reduction in the 12 regions can range from 0.97 kg/m^2 to 40.34 kg/m^2. According to the long-term carbon intensity reduction, the building in climate zone 1A has the greatest carbon intensity reduction potential among the three hot climate zones. From the long-term perspective, carbon emission reduction will decrease. However, the annual change in carbon emission does not always decrease and the impact of renewable energy technology capacity and increasing total electric load should be considered for long-term carbon emission reduction evaluation.

Acknowledgments

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Nomenclature

ΔX = energy consumption saving

X_base = energy consumption of the building before retrofits

X_retr = energy consumption of the building after retrofits

C = carbon emission reduction

Fx = emission factor

A = building floorspace

w = weighting factor of floor area

Subscripts

i = climate region

t = time with a unit (e.g. hour, minute)

n = building types

z_n = group of buidlings belonging to building type n

b_{z_n} = a building belonging to building type n

s = state

y = year

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