Pathways To Decarbonize the U.S. Medium-Sized Office Buildings in Cold Climates

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ABSTRACT

Buildings in cold climates have a high potential for carbon emission reduction due to the large difference between indoor and outdoor temperature. Existing research on carbon emission reduction of buildings in cold climates is case studies on a few locations. However, case studies cannot represent all cold climate regions because the available energy resources in different regions vary significantly. To fill this gap, we investigated the carbon emission reduction potential of building retrofits in cold climates of the United States (U.S.). The baseline building energy models are based on the Commercial Buildings Energy Consumption Survey, and the retrofitted building energy models are based on the Advanced Energy Design Guide 50% energy savings. Then, by simulating the baseline and retrofitted building energy models in cold climate regions, energy savings by retrofitting buildings can be predicted. Finally, the carbon emission reduction potential of building retrofits can be predicted by integrating energy savings with the emission factors of energy resources at corresponding times and states. This paper investigated the emission reduction potential for existing medium-sized office buildings in 18 states in cold climates of the U.S. from 2024 to 2050 under three different renewable energy cost scenarios. Based on the results, it is recommended that the retrofits of existing medium-sized office buildings in cold climates of the U.S. should focus on the buildings constructed before 1980 and the state of Utah, Michigan, Wisconsin, and Wyoming. Furthermore, the high renewable energy cost scenario has the most significant impact on the state of Iowa, while the low renewable energy cost scenario has the most significant impact on the state of Wisconsin.

1. INTRODUCTION

According to the 2012 Commercial Buildings Energy Consumption Survey (CBECS) data (CBECS 2016), the median site energy use intensity (EUI) of buildings in cold climates in the United States (U.S.) is 18% higher than buildings in other climates. As cold climate regions have higher EUI because of the high amount of required energy for heating in the long and cold winters, building envelope retrofits have critical effects on energy reduction (Aslani and Hachem-Vermette 2022). Furthermore, Lam et al. (2008) investigated building energy efficiency in different climates in China and found that passive solar designs would have a large energy savings potential in cold climates. Since buildings in cold climates have a high potential for energy reduction, they may also have a high potential for carbon emission reduction.

Case studies on carbon emission reductions of buildings in a few locations in cold climates were investigated by some

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researchers. Padovani et al. (2021) investigated the carbon emission reduction of rural residential buildings using Copper Harbor, Michigan as a representative location. Wang et al. (2022) investigated carbon emission reduction through carbon emission responsive building control using Basalt, Colorado as a case study. Our recent research also investigated the carbon emission reduction of building retrofits in a few locations in the cold climates in the U.S. (e.g., Great Falls in Montana, and International Falls in Minnesota).

However, case studies on carbon emission reduction cannot represent all cold climate regions because the available energy resources in different locations vary significantly. For example, Montana and Wisconsin are both in cold climates. However, the energy resource in these two states is significantly different. Clean energy accounts for approximately 51% of all electricity sold in Montana in 2021, thanks in large part to hydroelectric facilities (EIA 2022). However, only approximately 23% of electricity in Wisconsin comes from clean energy in 2021 (EIA 2022). Therefore, with the same amount of energy savings, the carbon emission reduction in these two states would be significantly different.

This research aims to predict the carbon emission reduction potential of the retrofits for medium-sized office buildings in cold climates of the U.S. The remainder of this paper is structured as follows. Section 2 introduces the research method to predict energy savings and carbon emission reductions. Section 3 illustrates the study design of this paper including investigated locations and building retrofit options. Section 4 presents the results of the carbon emission reduction potential of the retrofits for medium-sized office buildings in cold climates from three perspectives: the impact of locations, the impact of building construction years, and the impact of renewable energy cost scenarios. Finally, section 5 makes a conclusion.

2. METHOD

2.1. Energy Saving

According to the International Energy Conservation Code (IECC), cold climates in the U.S. include 6A (cold humid), 6B (cold dry), and 7 (very cold) (IECC 2022). The energy consumption of the building in the same climate zones is assumed to be the same. Furthermore, 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% (EIA 2018). Therefore, the energy saving due to retrofits for a building in climate region i can be expressed as the following equations:

$$E(i)_t = E\_base(i)_t - E\_\mathrm{retr}(i)_t, \tag{1}$$

$$N(i)_t = N\_base(i)_t - N\_\mathrm{retr}(i)_t, \tag{2}$$

where the E represents electricity consumption saving; the t represents time with a unit of one hour; the E_base represents the electricity consumption of the building before retrofits; the E_retr represents the electricity consumption of the building after retrofits; the N represents the natural gas consumption saving; the N_base represents the natural gas consumption of the building before retrofits; the N_retr represents the natural gas consumption of the building after retrofits. $E\_base(i)_t$, $E\_\mathrm{retr}(i)_t$, $N\_base(i)_t$, and $N\_\mathrm{retr}(i)_t$ are obtained by running the physical building energy models.

2.2. Carbon Emission Reduction

Based on our previous research (Lou et al. 2021, 2022), 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 in climate region i and state s can be expressed as the following equation:

$$C(i,s) = \left(\sum_{y=1}^{m} \sum_{t=1}^{n} E(i)_t \times Fe(s)_{y,t} + N(i)_t \times Fn \right) \div m, \tag{3}$$

where the C represents carbon emission reduction; the y represents time with a unit of one year; the m is the number of years that investigated in the research; the t represents time with a unit of one hour; the $n = 8784$ is the total number of hours in one year; the E and N represent electricity and natural gas consumption savings respectively, which are obtained from equations (1) and (2); the Fe represents the electricity emission factor, which is dynamically changing and assumed to be constant during the hour t (Gagnon et al. 2021); and the Fn represents the natural gas emission factor, which is 1.97 kg/m^3 (EIA 2021). The emission factors of electricity are determined by the renewable energy adoption rate in the corresponding time and locations. Due to the uncertainty of the future, three scenarios for renewable energy adoption introduced in the 2021 Standard Scenarios Report (Gagnon et al. 2021) will be investigated: mid-case (MidCase), high renewable energy cost (HighRECost), and low renewable energy cost (LowRECost).

3. STUDY DESIGN

3.1. Investigated Locations

Cold climates in the U.S. include 6A (cold humid), 6B (cold dry), and 7 (very cold), which covers 19 states in the U.S. (IECC 2022). Climate 7 includes some locations in Alaska. But the carbon emission factors in Alaska are not available. Therefore, Alaska is not investigated in this research. Considering the climate features and state, the cold climates in the U.S. can be divided into 25 regions, as shown in Figure 1.

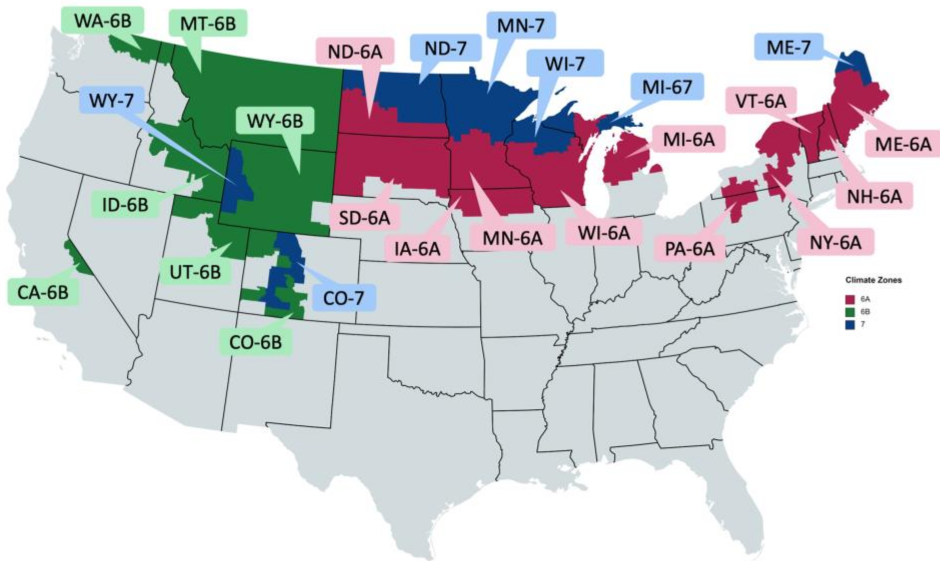

Figure 1 Locations investigated in this study. (CA: California; CO: Colorado; IA: Iowa; ID: Idaho; ME: Maine; MI: Michigan; MN: Minnesota; MT: Montana; ND: North Dakota; NH: New Hampshire; NY: New York; PA: Pennsylvania; SD: South Dakota; UT: Utah; VT: Vermont; WA: Washington; WI: Wisconsin; WY: Wyoming.)

These 18 states have distinct energy resources used for electricity generation, as shown in Figure 2. For example. California, Iowa, Maine, New Hampshire, New York, Vermont, and Washington hardly have coal used for electricity generation under all renewable energy adoption scenarios, while Utah adopts coal for more than 40% of electricity generation under all scenarios. Furthermore, Montana uses clean energy for almost 100% of electricity generation under MidCase and LowRECost scenarios.

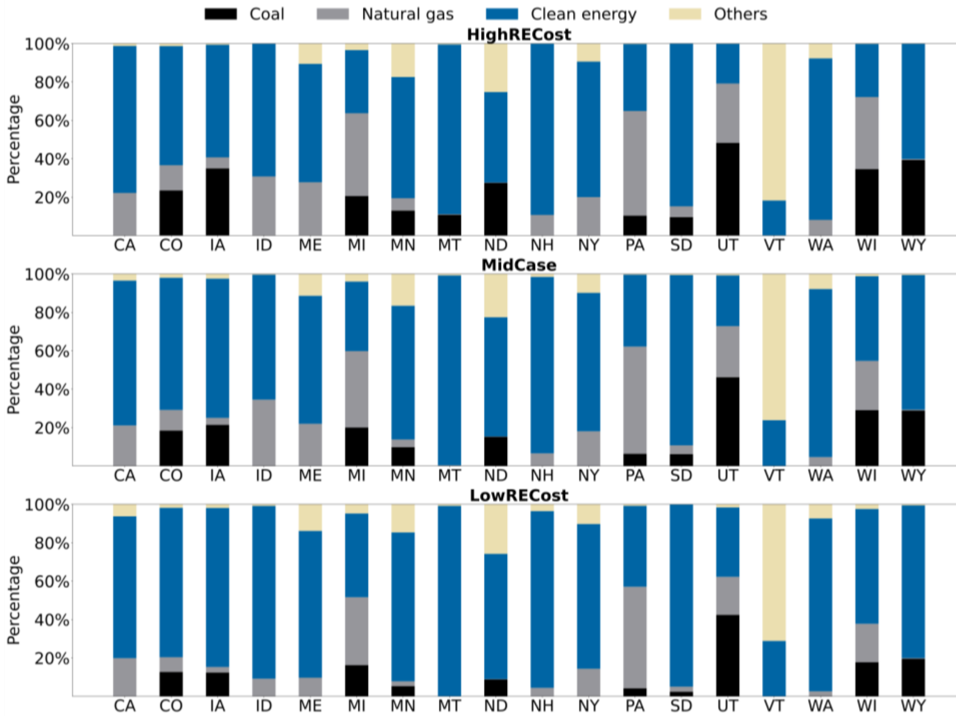

Figure 2 Average energy adoption rate for electricity generation from 2024 to 2050.

3.2. Building Retrofits

Based on our previous research (Lou et al. 2021, 2022; Ye et al. 2021), this study examined six building retrofit measures, which potentially have significant impacts on the carbon emissions of medium office buildings in cold climates. Table 1 shows these six retrofit measures. We examined the emission reduction potential of the aggregated effect of these six measures. One building retrofit model which applied these six measures is created. Buildings in a climate region are divided into two vintages: pre-1980 and post-1980. Vintage pre-1980 means that the building was constructed before 1980 and vintage post-1980 means that the building was constructed in or after 1980. Thus, there are 12 building energy models (3 climate locations × 2 vintages × (1 baseline model + 1 retrofit model)) in this study. The model input values of baseline models are based on the building energy model created based on the 2012 CBECS (Lou 2022). This medium office building energy model has one story with 3,437 m^2 total floor area and an 18% window-to-wall ratio. There are two types of energy used in this building energy model: electricity and natural gas. Natural gas is used for air conditioning system heating and service water heating. Electricity is used for others, such as air conditioning system cooling, zone supply air reheats, lighting, and equipment. The model input values of retrofitted models are based on the Advanced Energy Design Guide (AEDG) 50% energy savings (ASHRAE 2014).

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

Building Retrofit	Model Input	Unit	6A				6B				7			
			Pre 1980		Post 1980		Pre 1980		Post 1980		Pre 1980		Post 1980	
			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 insulation R-value	$ft^2 \cdot h \cdot °F/Btu$ ($m^2 \cdot K/W$)	7.72 (1.36)	18.23 (3.21)	15.44 (2.72)	18.23 (3.21)	7.72 (1.36)	18.23 (3.21)	15.44 (2.72)	18.23 (3.21)	8.12 (1.43)	18.23 (3.21)	15.84 (2.79)	18.23 (3.21)
Add roof insulation	Roof insulation R-value	$ft^2 \cdot h \cdot °F/Btu$ ($m^2 \cdot K/W$)	16.92 (2.98)	30.15 (5.31)	17.66 (3.11)	30.15 (5.31)	16.92 (2.98)	30.15 (5.31)	17.66 (3.11)	30.15 (5.31)	27.31 (4.81)	34.58 (6.09)	18.02 (3.35)	34.58 (6.09)

Replace windows	Window U-factor	Btu/h·ft^2·°F (W/m^2·K)	0.92 (5.24)	0.34 (1.93)	0.57 (3.26)	0.34 (1.93)	0.92 (5.24)	0.34 (1.93)	0.57 (3.26)	0.34 (1.93)	0.89 (5.04)	0.29 (1.65)	0.38 (2.18)	0.29 (1.65)
	Window SHGC	-	0.72	0.38	0.61	0.38	0.72	0.38	0.61	0.38	0.76	0.40	0.62	0.40
Improve lighting efficiency	Lighting power density	Btu/h·ft^2 (W/m^2)	6.88 (21.69)	2.18 (6.89)	5.17 (16.31)	2.18 (6.89)	6.88 (21.69)	2.18 (6.89)	5.17 (16.31)	2.18 (6.89)	6.88 (21.69)	2.18 (6.89)	5.17 (16.31)	2.18 (6.89)
Improve electric equipment efficiency	Plug load density	Btu/h·ft^2 (W/m^2)	4.21 (13.28)	2.56 (8.07)	2.64 (8.33)	2.56 (8.07)	4.21 (13.28)	2.56 (8.07)	2.64 (8.33)	2.56 (8.07)	4.21 (13.28)	2.56 (8.07)	2.64 (8.33)	2.56 (8.07)
Improve heating efficiency	Burner efficiency	-	0.72	0.81	0.77	0.81	0.72	0.81	0.77	0.81	0.72	0.81	0.77	0.81

[1] Base: Baseline models were created based on the 2012 CBECS (Lou 2022).

[2] Retr: Retrofit models were based on AEDG 50% energy saving (ASHRAE 2014).

4. RESULTS AND DISCUSSION

4.1. Impact of Locations

Figure 3 shows the annual carbon emission reduction potential of the retrofits for medium-sized office buildings from 2044 to 2050 in cold climates of the U.S. The top three emission reduction regions under the HighRECost scenario are Utah-6B, Wisconsin-6A, and Wyoming-6B. The top three emission reduction locations under the Midcase scenario are Utah-6B, Michigan-6A, and Wisconsin-6A. The top three emission reduction locations under the LowRECost scenario are Utah-6B, Michigan-6A, and Michigan-7. Therefore, Utah, Michigan, Wisconsin, and Wyoming are four locations that we should focus on to decarbonize the U.S. medium-sized office buildings in cold climates.

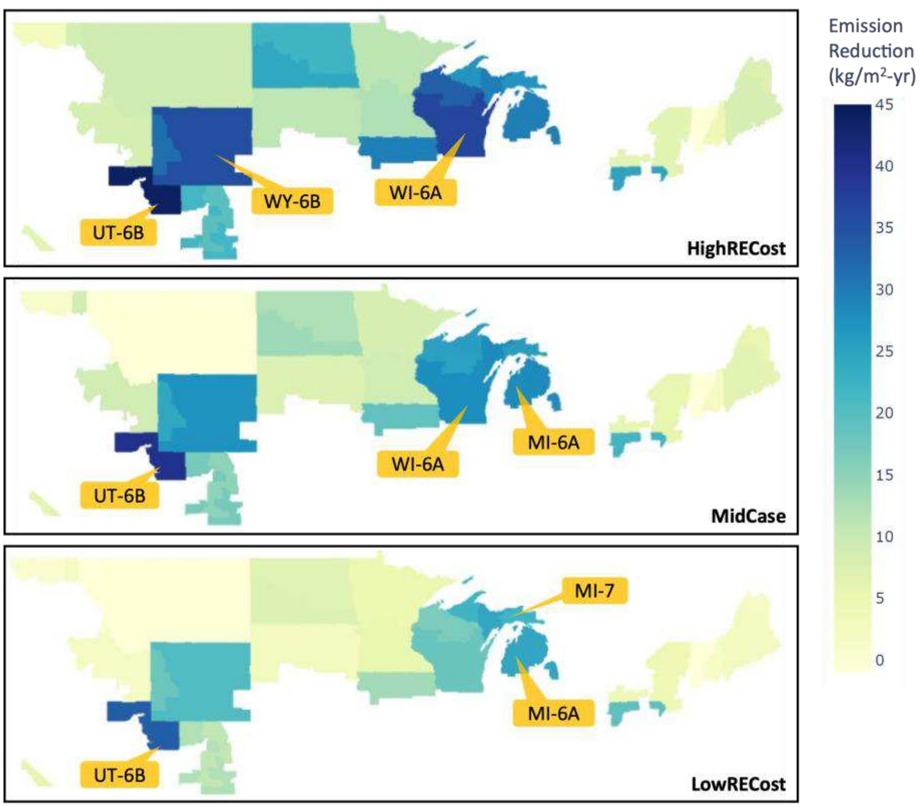

Figure 3 Annual carbon emission reduction potential of medium-sized office buildings from 2024 to 2050.

4.2. Impact of Building Construction Year

Figure 4 shows the difference of annual carbon emission reduction potential for the medium-sized office buildings constructed before 1980 and after 1980. Each dot in Figure 4 represents one region classified in Figure 1. The emission reduction potential of buildings constructed before 1980 is around 1.5 times higher than that constructed after 1980. This phenomenon is more significant for climate 7. Therefore, we should focus on buildings constructed before 1980 to decarbonize the U.S. medium-sized office buildings in cold climates. The buildings constructed before 1980 have higher lighting power density, electric equipment density, lower burner efficiency, and lower envelope insulation (Lou 2022). Therefore, with the same retrofitted value, buildings constructed before 1980 have more energy saving and emission reduction potential.

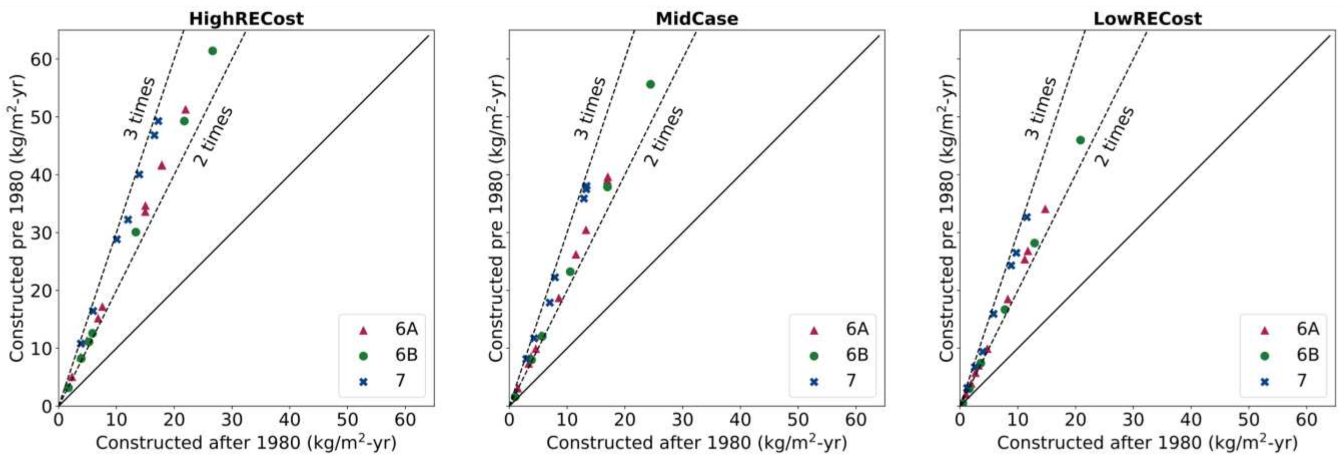

Figure 4 The difference of annual carbon emission reduction potential for medium-sized office buildings constructed before 1980 and after 1980.

4.3. Impact of Renewable Energy Cost Scenarios

Table 2 shows the impact of renewable energy cost scenarios on the annual carbon emission reduction potential of building retrofits in cold climate regions. In general, the HighRECost scenario increases the carbon emission reduction potential, while the LowRECost scenario decreases the carbon emission reduction potential. The HighRECost scenario discourages the adoption of renewable energy, which leads to higher electricity emission factors than the MidCase scenario. As a result, the same amount of energy saving will result in more carbon emission reduction potential. On the contrary, the LowRECost scenario encourages the use of renewable energy, which lead to lower electricity emission factors than the MidCase scenario. However, there is an exception in ID-6B where the HighRECost scenario decreases the carbon emission reduction potential. This is because the HighRECost scenario increases the clean energy adoption rate in Idaho (Figure 2). The total electricity generation under the HighRECost scenario decrease significantly in Idaho compared with the MidCase scenario, as shown in Figure 5. However, nuclear power and hydropower generation are relatively the same under the HighRECost and MidCase scenarios. As a combined effect, the nuclear and hydropower adoption rate under the HighRECost scenario is higher than that under the MidCase scenario.

Table 2. Impact of Renewable Energy Cost Scenarios on Annual Carbon Emission Reduction Intensity

Region	Emission Reduction lb/ft^2-yr (kg/m^2-yr)			Impact of HighRECost lb/ft^2-yr (kg/m^2-yr)	Impact of LowRECost lb/ft^2-yr (kg/m^2-yr)
	MidCase	HighRECost	LowRECost		
IA-6A	18.89 (3.87)	29.75 (6.10)	13.41 (2.75)	10.86 (2.23)	-5.48 (-1.12)
ME-6A	6.15 (1.26)	8.12 (1.66)	2.43 (0.50)	1.97 (0.40)	-3.72 (-0.76)
ME-7	5.54 (1.14)	7.33 (1.50)	2.18 (0.45)	1.79 (0.37)	-3.36 (-0.69)

MI-6A	28.36 (5.81)	29.79 (6.10)	24.43 (5.01)	1.43 (0.29)	-3.93 (-0.81)
MI-7	25.69 (5.26)	27.00 (5.53)	22.11 (4.53)	1.31 (0.27)	-3.58 (-0.73)
MN-6A	8.86 (1.82)	12.39 (2.54)	5.15 (1.06)	3.53 (0.72)	-3.71 (-0.76)
MN-7	8.02 (1.64)	11.21 (2.30)	4.67 (0.96)	3.19 (0.65)	-3.35 (-0.69)
NH-6A	2.29 (0.47)	3.70 (0.76)	1.55 (0.32)	1.41 (0.29)	-0.74 (-0.15)
NY-6A	5.37 (1.10)	6.16 (1.26)	4.23 (0.87)	0.79 (0.16)	-1.14 (-0.23)
ND-6A	13.66 (2.80)	24.32 (4.98)	7.33 (1.50)	10.66 (2.18)	-6.33 (-1.30)
ND-7	12.45 (2.55)	22.12 (4.53)	6.66 (1.36)	9.67 (1.98)	-5.79 (-1.19)
PA-6A	21.88 (4.48)	24.85 (5.09)	19.30 (3.95)	2.97 (0.61)	-2.58 (-0.53)
SD-6A	7.27 (1.49)	11.02 (2.26)	2.93 (0.60)	3.75 (0.77)	-4.34 (-0.89)
VT-6A	-0.63 (-0.13)	-0.62 (-0.13)	-0.63 (-0.13)	0.01 (0.00)	0.00 (0.00)
WI-6A	28.02 (5.74)	36.64 (7.51)	18.31 (3.75)	8.62 (1.77)	-9.71 (-1.99)
WI-7	25.40 (5.20)	33.26 (6.82)	16.58 (3.40)	7.86 (1.61)	-8.82 (-1.81)
CA-6B	5.92 (1.21)	6.07 (1.24)	5.52 (1.13)	0.15 (0.03)	-0.40 (-0.08)
CO-6B	16.89 (3.46)	21.71 (4.45)	12.23 (2.51)	4.82 (0.99)	-4.66 (-0.95)
CO-7	15.08 (3.09)	19.45 (3.99)	10.87 (2.23)	4.37 (0.90)	-4.21 (-0.86)
ID-6B	8.88 (1.82)	8.17 (1.67)	2.31 (0.47)	-0.71 (-0.15)	-6.57 (-1.35)
MT-6B	-0.61 (-0.13)	9.23 (1.89)	-0.71 (-0.15)	9.84 (2.02)	-0.10 (-0.02)
UT-6B	40.04 (8.20)	44.03 (9.02)	33.42 (6.85)	3.99 (0.82)	-6.62 (-1.36)
WA-6B	1.31 (0.27)	2.44 (0.50)	0.49 (0.10)	1.13 (0.23)	-0.82 (-0.17)
WY-6B	27.44 (5.62)	35.51 (7.28)	20.55 (4.21)	8.07 (1.65)	-6.89 (-1.41)
WY-7	24.4 (5.00)	31.70 (6.50)	18.12 (3.71)	7.30 (1.50)	-6.28 (-1.29)

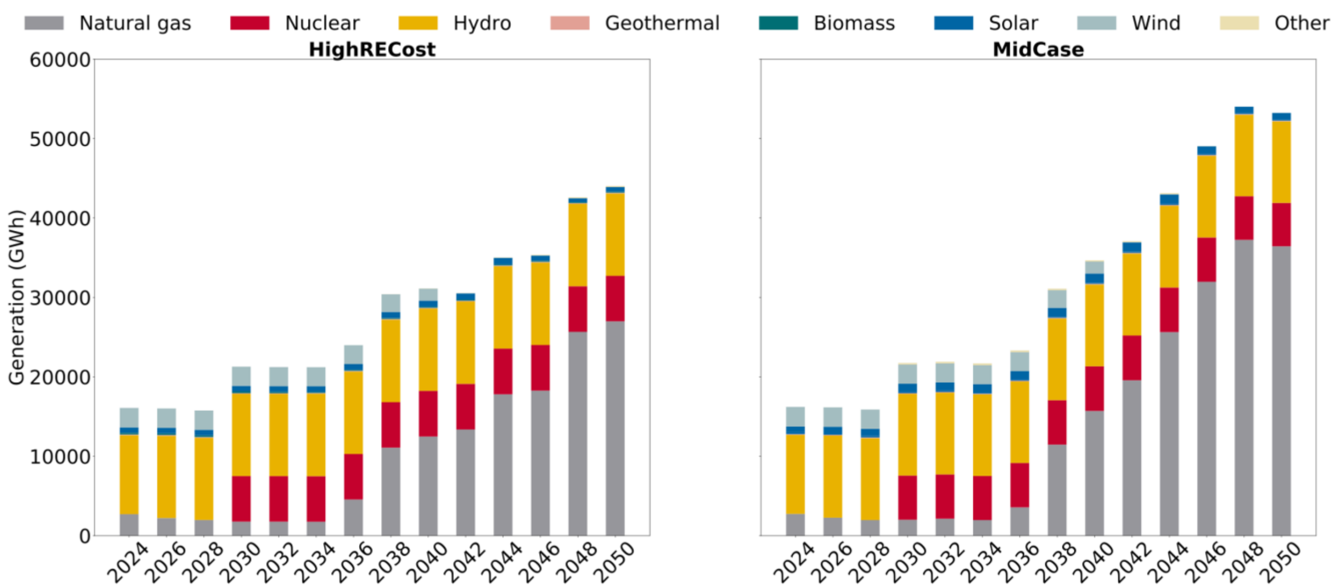

Figure 5 Electricity generation by source in Idaho.

5. CONCLUSION

This research predicted the carbon emission reduction potential of the retrofits for existing medium-sized office buildings in cold climates. To represent all cold climates, we divided the cold climate area in the U.S. into 25 regions considering the climate features and clean energy adoption rates. We analyzed the emission reduction potential of building retrofits in the cold climate in the U.S. from 2024 to 2050 under three different renewable energy cost scenarios. Based on the results, it is recommended that to decarbonize the U.S. medium-sized office buildings in cold climates, we should focus on: (1) the state of Utah, Michigan, Wisconsin, and Wyoming; (2) buildings constructed before 1980; and (3) states under the high renewable cost scenario. In the future, the investments and cost savings of each building retrofit measure will be investigated to identify the most cost-effective measure.

ACKNOWLEDGMENTS

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NOMENCLATURE

E	=	electricity consumption saving
E_base	=	electricity consumption of the building before retrofits
E_retr	=	electricity consumption of the building after retrofits
N	=	natural gas consumption saving
N_base	=	natural gas consumption of the building before retrofits
N_retr	=	natural gas consumption of the building after retrofits
C	=	carbon emission reduction
Fe	=	electricity emission factor
Fn	=	natural gas emission factor

Subscripts

t	=	time with a unit of one hour
y	=	time with a unit of one year
n	=	the total number of hours in one year
m	=	the number of years that investigated in the research
i	=	climate region
s	=	state

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