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The effect of building retrofit measures on CO_2 emissions reduction – A case study with U.S. medium office buildings

Yingli Lou[a], Yizhi Yang[a], Yunyang Ye[b], Wangda Zuo[a,c,*], Jing Wang[a]

[a] Department of Civil, Environmental and Architectural Engineering, University of Colorado Boulder, Boulder, CO 80309, U.S.A.

[b] Pacific Northwest National Laboratory, Richland, WA 99354, U.S.A.

[c] National Renewable Energy Laboratory, Golden, CO 80401, U.S.A

* Corresponding author. Email address: Wangda.Zuo@colorado.edu (Wangda Zuo)

Abstract

Building retrofits have great potential to reduce CO_2 emissions since buildings are responsible for 36% of emissions in the United States. Several existing studies have examined the effect of building retrofit measures on CO_2 emission reduction. However, these studies oversimplified emission factors of electricity by adopting constant annual emission factors. This study uses hourly emission factors of electricity to analyze the effect of building retrofit measures on emission reduction using U.S. medium office buildings as an example. We analyzed the CO_2 emission reduction effects of eight building retrofit measures that related to envelope and mechanical systems in five locations: Tampa, San Diego, Denver, Great Falls, and International Falls. The main findings are: (1) estimating CO_2 emission reduction with constant emission factors overestimates the emission reduction for most measures in San Diego, while it underestimates the emission reduction for most measures in Denver and International Falls; (2) The same retrofit measure may have different effects on CO_2 emission reduction depending on the climate. For instance, *improving lighting efficiency* and *improving equipment efficiency* have less impact in emission reduction in cold climates than hot climates; and (3) The most energy efficient measure may not be the most efficient emission measure. For example, in Great Falls, the most energy efficient measure is *improving equipment efficiency*, but the most efficient emission measure is *improving heating efficiency*.

Keywords: CO_2 emissions, Building, Retrofit, Building energy model, Simulation

1. Introduction

The United States (U.S.) is the second-largest contributor to CO_2 emissions [1] and reducing emissions in the U.S. is necessary to mitigate the risk of catastrophic climate change. Intergovernmental Panel on Climate Change (IPCC) declared that the CO_2 emissions humans spew into the atmosphere leads to climate change. By the end of the 21st century, the current CO_2 emissions will cause global warming to around 1.5–2 °C if we do not drastically limit CO_2 emissions by mid-century and beyond [2]. Global warming is associated with many physical and biological damages, such as receding glaciers, bleached corals, acidifying oceans, killer heat waves, and hurricanes [3][4][5]. The U.S. outlined a pathway to reduce CO_2 emissions by 50% below 2005 levels by 2030 [6], and 80% below 2005 levels by 2050 [7].

Buildings are critical for emission reduction because the U.S. buildings sector accounted for 36% of energy-related CO_2 emissions [8]. At present, there are plenty of buildings have poor energy performance and lead to a bulk of CO_2 emissions [9][10]. Most of these buildings will still be in function until 2025 or even 2050 [11]. Retrofitting existing buildings is crucial for emission reduction in the U.S. Langevin et al. [12] found that the combination of aggressive efficiency measures, electrification, and high renewable energy penetration can reduce CO_2 emissions in the U.S. building sector by 72%–78% relative to 2005 levels.

Several existing studies have examined the CO_2 emission reduction effect of building retrofit measures. In the case study conducted by Tettey et al. [13], CO_2 emission reduction is about 6–8% when the building insulation material is changed from rock wool to cellulose fiber. Murray et al. [14] treated CO_2 emission factors of electricity as an uncertainty variable and investigated the optimal set of building measures to minimize emissions for the Swiss building stock. An average CO_2 emission factor of electricity in Spain was adopted by Garriga et al. [15] to study the optimal carbon-neutral retrofit of residential communities in Barcelona, Spain. Huang et al. analyzed the CO_2 emission payback periods of external overhang shading in a university campus in Hong Kong [16]. An average emission factor of electricity in recent years in Hong Kong was adopted in this research. An average emission factor of electricity in the last five years in Finland was used by Niemelä et al. [17] to determine the cost-optimal renovation from the CO_2 emission reduction potential perspectives. Life-cycle CO_2 emission reduction of retrofit measures in new commercial buildings was studied by Kneifel and a state-level annual emission factor of electricity was adopted in this study [18].

However, the CO_2 emission factor of electricity is oversimplified in existing studies and a constant factor throughout the whole year is adopted. In fact, the emission factors can potentially change every day, even every hour, especially in areas with a high renewable energy penetration [19][20][21]. For example, if solar power generation is prevalent in one area, CO_2 emission factors of electricity will be low during the daytime and high at nighttime. If a region has extensive hydropower generation, emission factors of electricity will be lower during the rainy season than the dry season. As a result, using a constant average emission factor may underestimate or overestimate the emission reduction of some building retrofit measures.

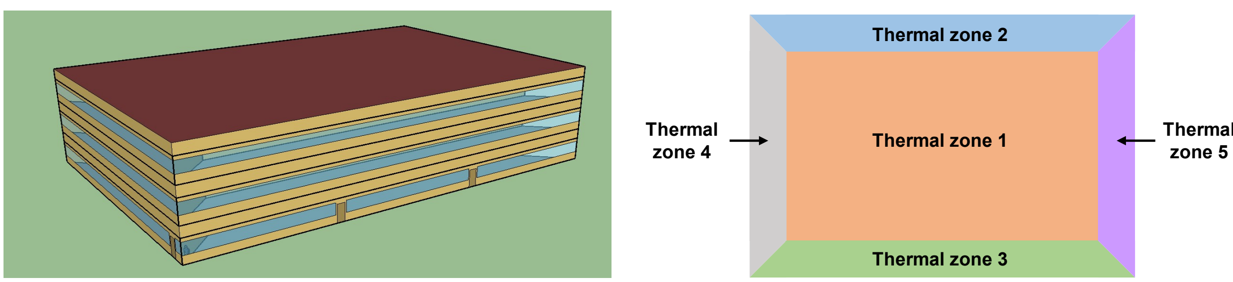
The above literature review shows that there is a lack of study on the emission reduction of building retrofit measures with dynamically changing electricity emission factors. Existing research adopted a constant emission factor, while electricity emission factors are dynamically changing. The impact of electricity emission factors on building emissions is significant since electricity is the major energy source of buildings. Therefore, it is crucial to investigate the emission reduction difference between using dynamically changing emission factors and a constant factor.

In this study, hourly CO_2 emission factors of electricity are adopted to analyze the effect of building retrofit measures on emission reduction. U.S. medium office buildings are used as an example in this study.

This paper is organized as follows: Section 2 introduces the design of the case study including location selection, building retrofit measures selection, and the method to estimate the emission reduction effect of individual measures. Section 3 presents the hourly CO_2 emission reduction by applying individual measures using one location as an example. And the annual CO_2 emission reduction effect of individual measures in all locations is analyzed in Section 3. Section 4 discusses the impact of climates on emission reduction effect, the difference between energy efficient measures and emission efficient measures, and the difference between using the hourly CO_2 emission factors of electricity and the annual factor. Finally, interesting findings are concluded in Section 5.

2. Study Design

This section first introduces studied locations and building retrofit measures. Then, we introduce the method to estimate the CO_2 emission reduction effect of individual measures. To support commercial and residential building energy codes and standards, the U.S. Department of Energy (DOE) has been dedicating to the development of prototype building models. The prototype models include 16 commercial building types in 19 climate locations (16 in the U.S. and 3 international locations) for different editions of ASHRAE Standard 90.1 and IECC. Those models are widely used to investigate energy saving [22][23][24][25][26][27], power consumption [28][29], and emission reduction [18]. And the results based on these models are also accepted by the community. Therefore, this study adopted DOE Commercial Prototype Building Models for medium office buildings [30] to estimate CO_2 emissions. Fig. 1 shows the geometry and thermal zones of the model, which has a rectangular shape with three stories. Each story contains five thermal zones. Table 1 summarizes the key model parameters.



(a) Geometry (b) Thermal zones (each floor)

Fig. 1. building model Geometry and thermal zones of the prototype medium office building model

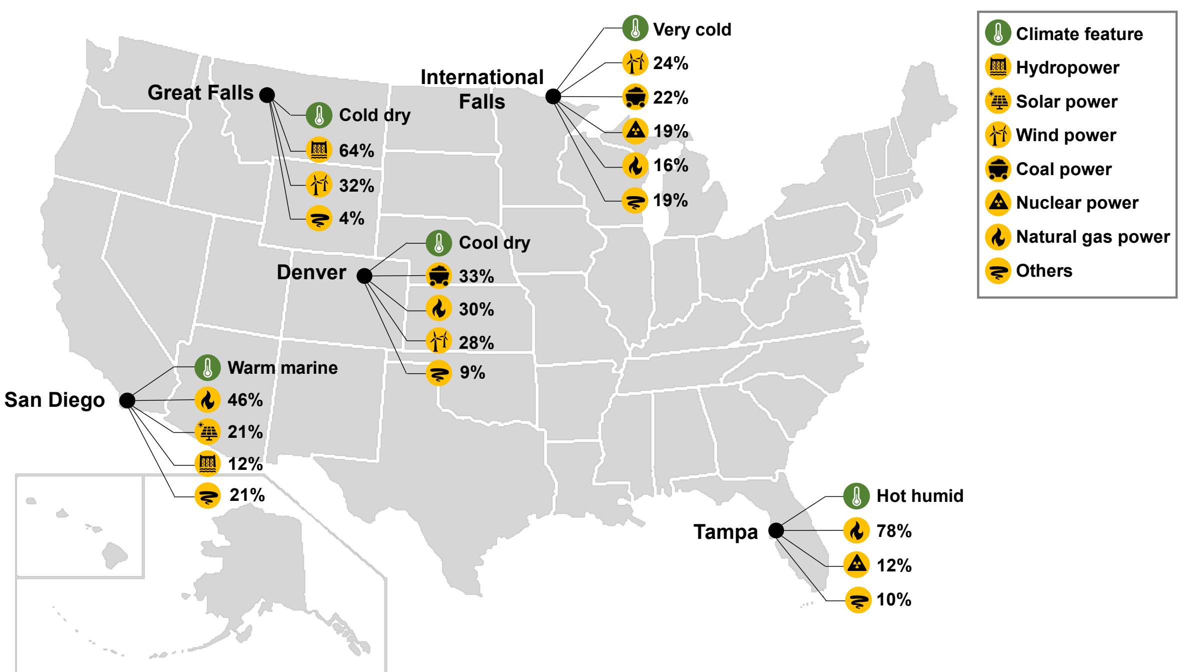
Table 1. Key parameters of the prototype medium office building model

Parameter Name	**Value**
Total floor area	4982 m^2 (49.91 m × 33.27 m × 3)
Aspect ratio	1.5
Number of floors	3
Window-to-wall ratio	33%
Floor-to-floor height	3.96 m
Envelope type	Exterior walls: steel-frame walls Roof: insulation above deck
HVAC system type	Heating: gas furnace inside the packaged air conditioning unit

Parameter Name	Value
	Cooling: packaged air conditioning unit Terminal Units: VAV terminal box with damper and electric reheating coil
Service water heating type	Storage tank using natural gas as fuel

2.1. Location selection

The selected locations should cover different climates and compositions of electricity generation. Using this principle, five locations are selected: (1) Tampa, Florida; (2) San Diego, California; (3) Denver, Colorado; (4) Great Falls, Montana; and (5) International Falls, Minnesota. As shown in Fig. 2, they represent five different climates (from hot humid to very cold). Their compositions of electricity generation vary from fossil fuel dominated (e.g., Tampa) to renewable energy dominated (e.g., Great Falls). The consumption of fossil fuel, like coal and natural gas, produces direct CO_2 emissions, while the consumption of renewable energy, like hydropower, solar power, wind power, and nuclear, doesn't produce direct emissions.



Note: Climate features are obtained from [30]; compositions of electricity generation are obtained from [31].

Fig. 2. Locations selection for the case study

2.2. Building retrofit measure selection

This subsection introduces building retrofit measures that are examined in this study. Existing research has provided a rich set of building retrofit measures for U.S. commercial buildings [32][33][27][34][35][36]. Based on our previous research [23][22], eight building retrofit measures for U.S. medium office buildings are included in this study, as shown in Table 2. Based on literatures [22], these eight building retrofit measures potentially have significant impacts on the CO_2 emissions for medium office buildings across different climate feature locations. The abbreviation for each measure will be used in the rest of this paper. The values of model inputs will be introduced in Section 2.3.

Table 2. Building retrofit measures examined in the case study

No.	Building Retrofit Measure	Abbreviation	Model Input
1	Add wall insulation	WALL	Wall insulation R-value
2	Add roof insulation	ROOF	Roof insulation R-value
3	Replace windows	WINDOW	Window U-factor, Window SHGC
4	Replace interior lights with higher efficiency lights	LIGHT	Lighting power density
5	Replace office equipment with higher efficiency equipment	EQUIP	Plug load density
6	Replace cooling coil with higher efficiency coil	COOLING	Nominal coefficient of performance (COP)
7	Replace heating burner with higher efficiency burner	HEATING	Burner efficiency
8	Replace service hot water system with higher-efficiency system	SWH	Heater thermal efficiency

2.3 CO_2 emission reduction

The CO_2 emission reduction effect of the individual measure (R_i) can be obtained using the following formula:

$$R_i = \frac{C_0 - C_i}{C_0} \times 100\%, \quad i = 1,2,3,4,5,6,7,8, \tag{1}$$

where, C_o is CO_2 emissions of baseline building model; and C_i is CO_2 emissions of retrofit building model by applying the retrofit measure i. The C_0 and C_i can be obtained using the following formula, which is also illustrated in Fig. 3.

$$C_i = \sum_{t=1}^{n} C_{i,t} = \sum_{t=1}^{n} (Ce_{i,t} + Cn_{i,t}) = \sum_{t=1}^{n} (E_{i,t} \times Fe_t + N_{i,t} \times Fn), \tag{2}$$

where, $C_{i,t}$ is CO_2 emissions at time t for the building with retrofit measure i. For the baseline building, $i = 0$. The n is the total number of hours in a year, which is 8784 in this study. The $Ce_{i,t}$ is CO_2 emissions from electricity at time t for the building with retrofit measure i. The $Cn_{i,t}$ is CO_2 emissions from natural gas at time t for the building with retrofit measure i. The $E_{i,t}$ is electricity consumption at time t for the building with retrofit measure i. The Fe_t is electricity CO_2 emission factor at time t. $N_{i,t}$ is natural gas consumption at time t for the building with retrofit measure i. Fn is natural gas emission factor, which is a constant value.

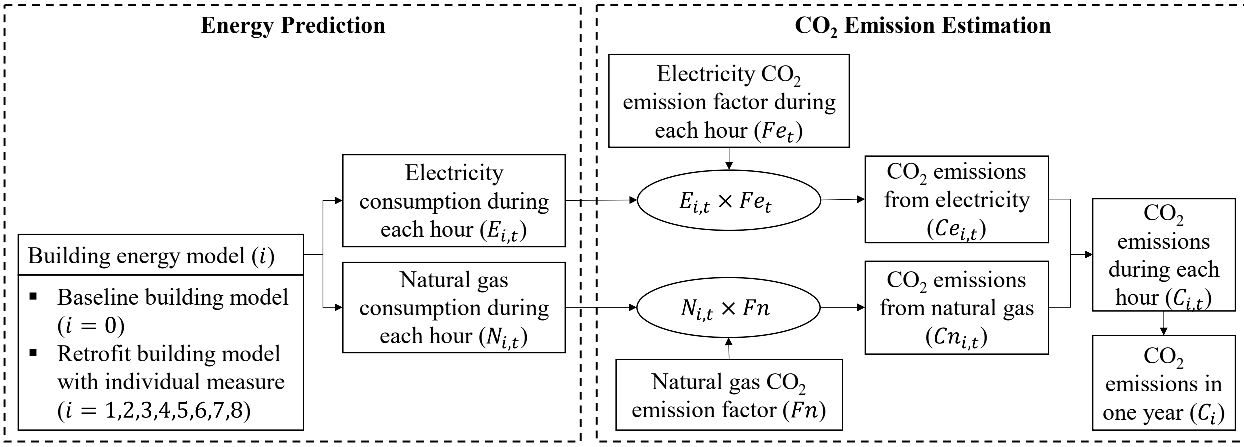


Fig. 3. Workflow to estimate the CO_2 emissions of a building

The model input values of baseline models are based on ASHRAE Standard 90.1-2007 [37]. The model input values of retrofit models are based on the Advanced Energy Design Guide 50% Energy Savings [38]. Table 3 shows the model input values of baseline models and retrofit models, which result in 45 models (5 locations × (1 baseline model + 8 retrofit models)). The objective of this study is to investigate the emission reduction effect due to building retrofit measures on different locations. Therefore, the embodied emissions of building retrofit measures are not involved in this study.

Table 3. Model input values of baseline models and retrofit models

Model Input	**Unit**	**Tampa**		**San Diego**		**Denver**		**Great Falls**		**International Falls**	
		Base[1]	**Retr[2]**	**Base[1]**	**Retr[2]**	**Base[1]**	**Retr[2]**	**Base[1]**	**Retr[2]**	**Base[1]**	**Retr[2]**
Wall insulation R-value	m^2-K/W	1.04	2.75	1.71	2.75	2.37	4.19	2.37	4.76	2.37	4.76
Roof insulation R-value	m^2-K/W	3.47	4.52	3.47	4.52	3.47	5.50	3.47	5.50	3.47	6.29
Window U-factor	W/m^2-K	4.09	2.56	3.52	2.33	2.73	1.99	2.73	1.99	2.38	1.87
Window SHGC	-	0.25	0.25	0.25	0.25	0.4	0.26	0.4	0.35	0.45	0.40
Lighting power density	W/m^2	10.76	8.07	10.76	8.07	10.76	8.07	10.76	8.07	10.76	8.07
Plug load density	W/m^2	8.07	5.92	8.07	5.92	8.07	5.92	8.07	5.92	8.07	5.92
Nominal COP	-	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37	3.23	3.37
Burner efficiency	-	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90	0.80	0.90
Heater thermal efficiency	-	0.81	0.90	0.81	0.90	0.81	0.90	0.81	0.90	0.81	0.90

[1] Base: Baseline model (Source: ASHRAE Standard 90.1–2007 [37])
[2] Retr: Retrofit model (Source: AEDG 50% Energy Savings [38])

2.3.1. Energy prediction

As shown in Fig. 3, this study predicts energy consumption for (1) baseline building models and (2) retrofit building models by adopting individual measures. In this study, the baseline models are the DOE Commercial Prototype Building Models for medium office buildings [30], which were introduced in the beginning of Section 2. Retrofit models are the updated baseline models by adopting the individual measures listed in Table 2. The model input values of individual measures are listed in Table 3. Two types of data are extracted after model simulation: (1) hourly electricity consumption ($E_{i,t}$) and (2) hourly natural gas consumption ($N_{i,t}$).

2.3.2. CO_2 emission estimation

Using the electricity and gas consumption data obtained in the subsection 2.3.1, this subsection introduces the method to estimate CO_2 emissions of baseline models and retrofit models. As shown in Fig. 3, CO_2 emissions from electricity are calculated by multiplying hourly electricity consumption with hourly emission factors of electricity, and CO_2 emissions from natural gas are calculated by multiplying hourly natural gas consumption with one natural gas emission factor. Hourly CO_2 emission factors of electricity are obtained from the National Renewable Energy Laboratory (NREL) website [31]. The emission factor in each hour is the average values of emission factors during that hour. For example, Fig. 4 shows the hourly emission factors of electricity in Great Falls. The horizontal axis in Fig. 4 represents each day of the year. Vertical axis represents each hour of the day. The shade of the color represents the magnitude of the value in a specific hour on one day. Fig. 5 shows hourly emission factors of electricity on two typical days (summer day: 2020-06-19 and winter day 2020-12-21) for the five studied locations. Hourly emission factors of electricity in Great Falls during the summer are almost always zero because there is abundant hydropower during that time. The natural gas emission factor is a fixed value in the whole year for five studied locations, which is 180 kg/MWh [39].

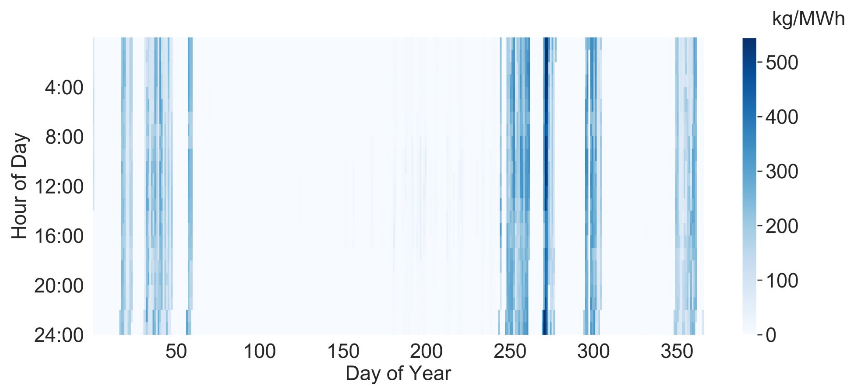
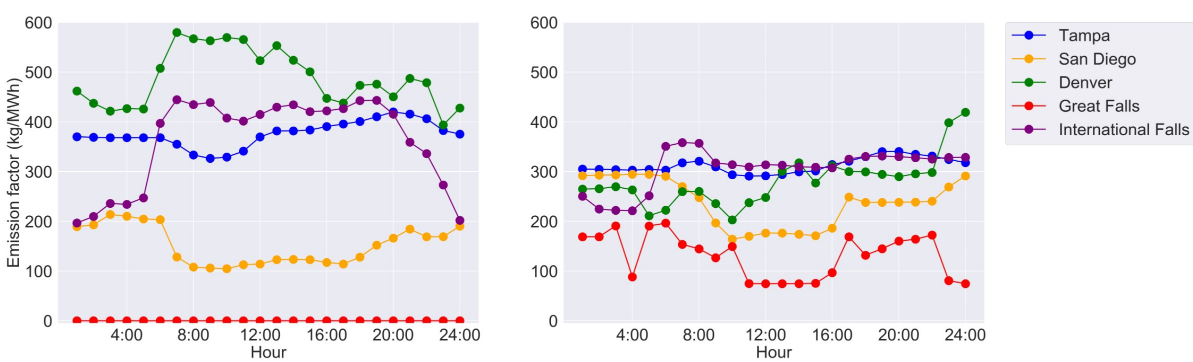


Fig. 4. Hourly CO_2 emission factors of electricity in Great Falls



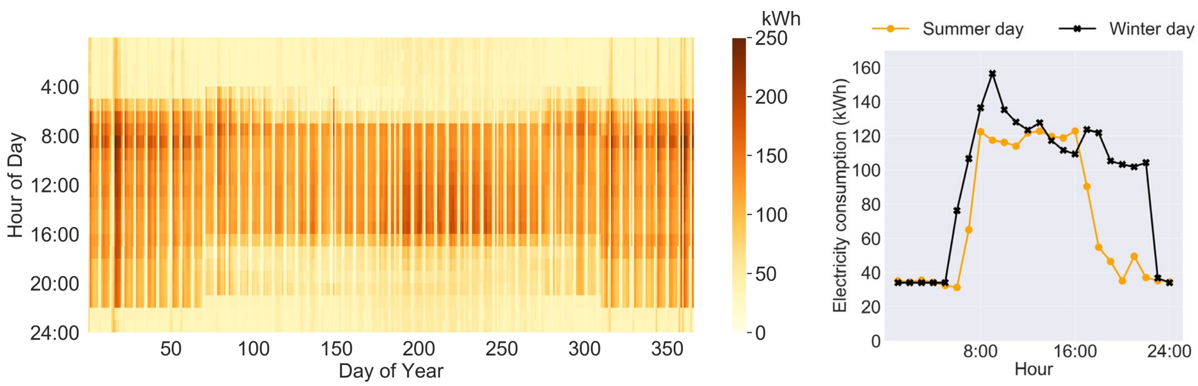
(a) Summer day (b) Winter day

Fig. 5. Hourly CO_2 emission factors of electricity on two typical days

3. Results

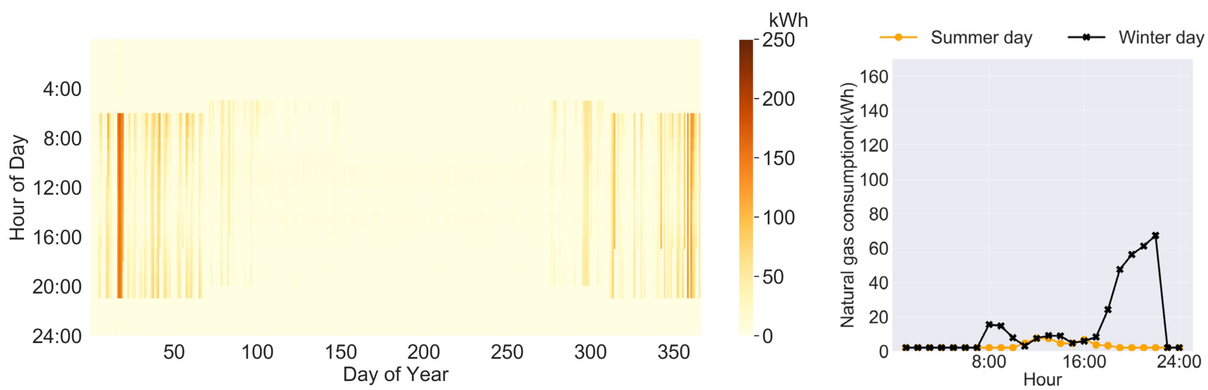
3.1. Energy prediction

This subsection shows the prediction results of hourly electricity and natural gas consumption in 2020 for the baseline models and retrofit models. We use the baseline model in Great Falls as an example to illustrate the hourly electricity and natural gas consumption, as shown in Fig. 6 and Fig. 7. To make the two types of energy consumption comparable, the unit of natural gas consumption is converted from MJ to kWh. Fig. 6 (a) and Fig. 7 (a) shows that the electricity consumption is much higher than the natural gas consumption in Great Falls. Electricity consumption is relatively even throughout the year, while natural gas consumption primarily concentrates in winter. Fig. 6 (a) and Fig. 7 (a) also shows that there is a periodic change in the electricity and natural gas consumption: electricity and natural gas consumption is intensive during the workday, while they are almost zero over the weekend. Fig. 6 (b) and Fig. 7 (b) shows that electricity consumption is concentrated from 7:00 to 22:00 in winter and 8:00 to 16:00 in summer; natural gas consumption is concentrated from 8:00 to 22:00 in winter and almost no consumption in summer.



(a) Whole year (b) Two typical days

Fig. 6. Hourly electricity consumption of the baseline model in Great Falls

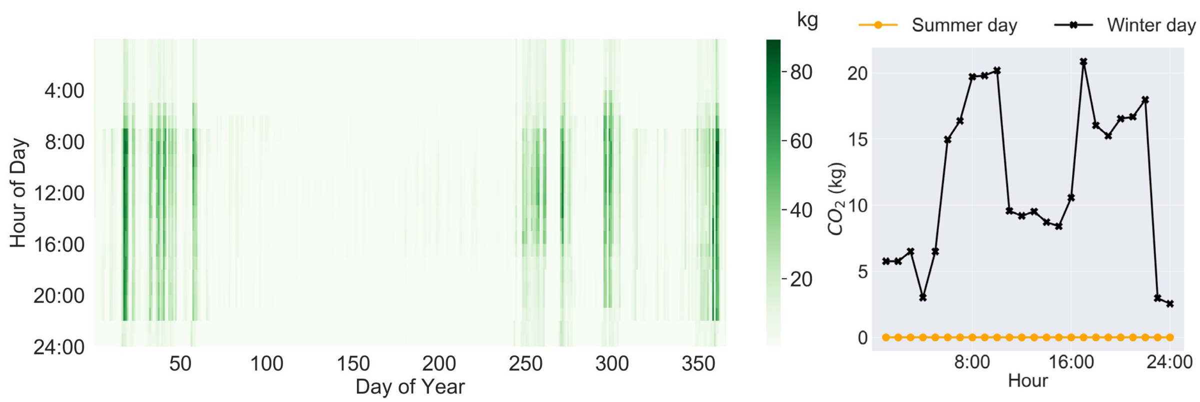


(a) Whole year (b) Two typical days

Fig. 7. Hourly natural gas consumption of the baseline model in Great Falls

3.2. CO_2 emission estimation

Based on the hourly electricity and natural gas consumption predicted in subsection 3.1, hourly CO_2 emissions of baseline models and retrofit models in five locations can be obtained using equation (2). Here we use Great Falls as an example to discuss the relationship between energy consumptions and CO_2 emissions. The hourly CO_2 emissions of the baseline model in Great Falls is shown in Fig. 8. There are some interesting findings in two different time scales for Great Falls.



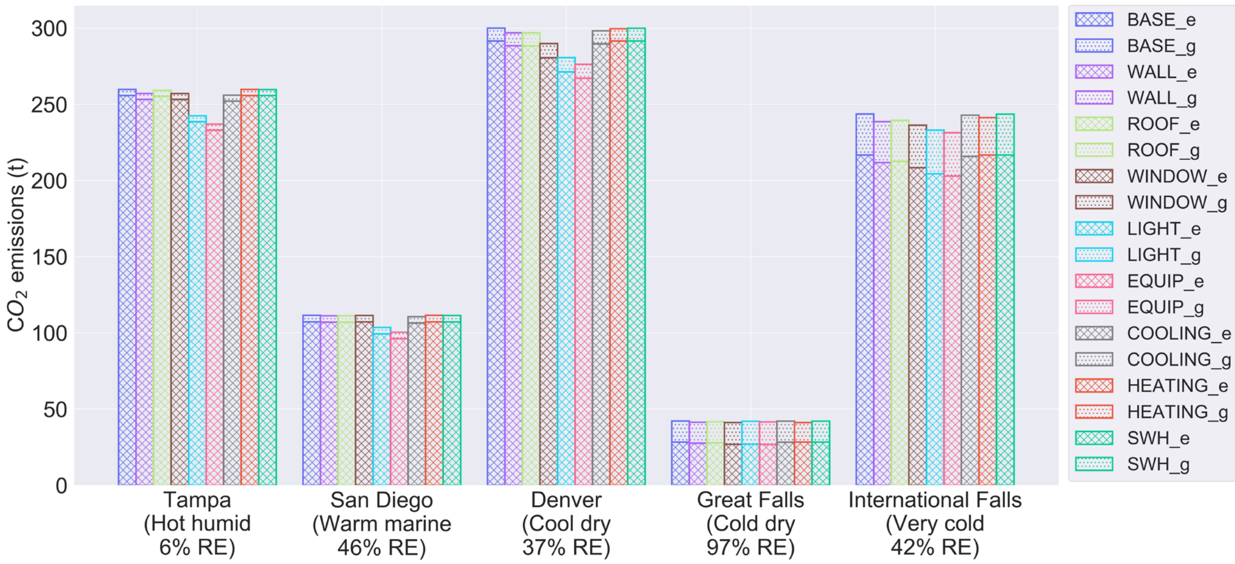
(a) Whole year (b) Two typical days

Fig. 8. Hourly CO_2 emissions of the baseline model in Great Falls

For a period of one year, the change of CO_2 emissions is not consistent with the energy consumption. The emissions in Great Falls mainly occur on some days during winter while almost always zero during summer. On the contrary, Fig. 6 (a) shows that electricity consumption is intensive during the whole year in Great Falls. This inconsistency is due to time-variant emission factors: hourly CO_2 emission factors of electricity in Great Falls are almost always zero during summer and high in winter, as shown in Fig. 4. As a result, the emissions from electricity consumption in summer are almost always zero despite the amount of electricity consumption. Emissions from natural gas are also almost always zero during summer due to low natural gas consumption as shown in Fig. 7. Therefore, total CO_2 emissions in Great Falls during summer are almost always zero.

For a period of one whole day in winter, the variation of CO_2 emissions (Fig. 8) is consistent with energy consumption (Fig. 6 and Fig. 7): emissions from the building mainly happen during the daytime, as shown in Fig. 8, and energy consumption from the building also mainly happens during the daytime, as shown in Fig. 6 and Fig. 7. This is because hourly emission factors of electricity in Great Falls on one whole day are relative constant (Fig. 4) and the natural gas emission factor is a constant value. It is worth noting this phenomenon may not occur for other locations, such as San Diego, where electricity is largely provided by solar.

Fig. 9 shows the annual CO_2 emissions of baseline building models and retrofit building models in five studied locations. "MEASURE_e" represents emissions from electricity and "MEASURE_g" represents emissions from natural gas. There are some interesting findings among different locations.



Note: Renewable energy (RE) penetration is obtained from [31].

Fig. 9. Annual CO_2 emissions of baseline models and retrofit models

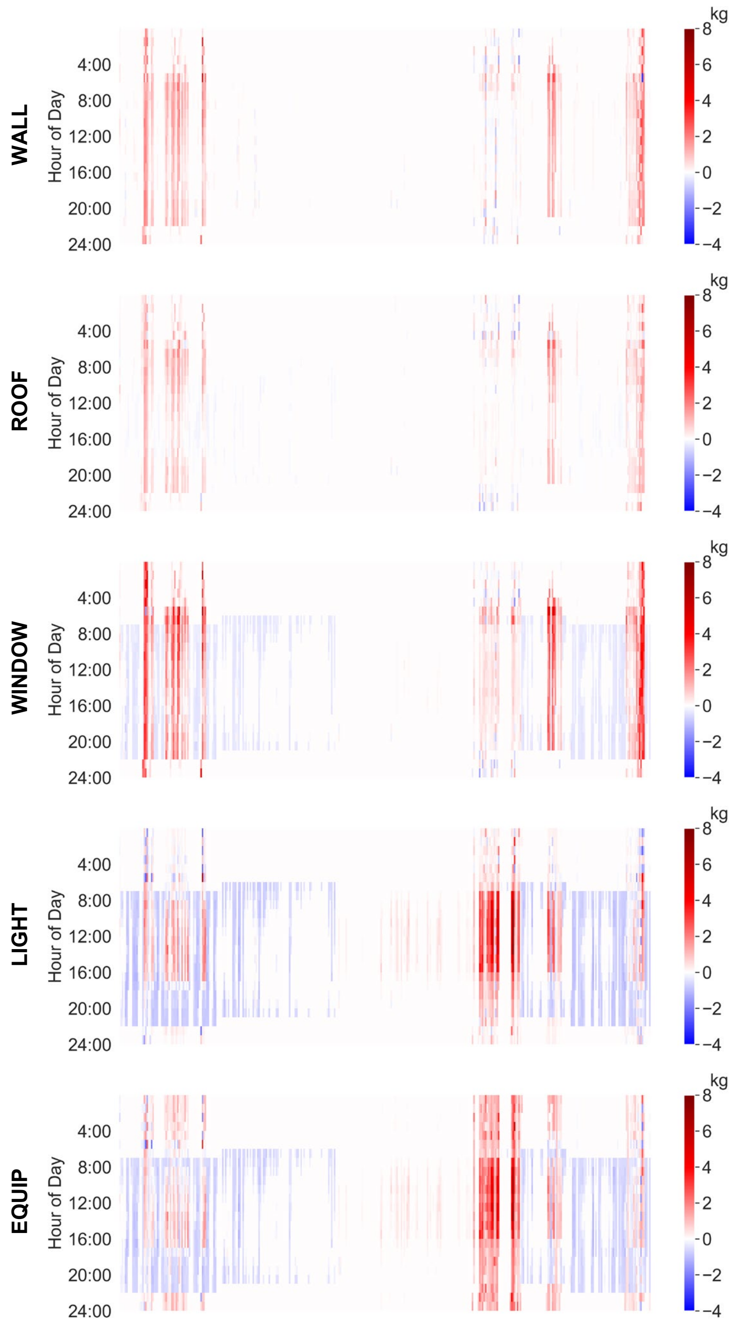
First, the CO_2 emissions in San Diego and Great Falls are much lower than the other three locations. This is because San Diego and Great Falls have high renewable energy penetration, which is 46% and 97% respectively.

Moreover, International Falls has the largest CO_2 emissions from natural gas, followed by Great Falls, Denver, San Diego, and Tampa. CO_2 emissions from natural gas increase as the climate gets colder since natural gas is used for heating. When the climate gets colder, heating loads increase accordingly [40][41]. So, natural gas consumption for heating increases when the climate gets colder, which leads to the increase of CO_2 emissions.

The CO_2 emissions from natural gas only account for a small part of total emissions in Tampa, San Diego, Denver, and International Falls, but they account for more than 30% of total emissions in Great Falls, as shown in Fig. 9. One of the reasons is that natural gas consumption in Great Falls is large due to the cold climate feature mentioned above. Another reason is that hourly emission factors of electricity in Great Falls are very low due to the high penetration of hydropower and wind power.

3.3. CO_2 emission reduction

CO_2 emission reduction by applying individual measures can be obtained by subtracting emissions of the retrofit building from emissions of the baseline building. For example, CO_2 emission reductions by applying individual measures in Great Falls are shown in Fig. 10. Red means this measure reduces emissions, while blue indicates the increase of emissions. Fig. 10 shows that: (1) building retrofit measures in Great Falls reduce CO_2 emissions in winter due to the high emission factors of electricity; (2) HEATING reduces CO_2 emissions more significantly than the other seven measures since natural gas is used for heating; (3) COOLING hardly reduces CO_2 emissions since emission factors of electricity in summer are almost zero when cooling is needed; (4) SWH also has little impact on CO_2 emissions because only a little amount of energy is used for service water heating; (5) by improving the efficiency, LIGHT and EQUIP reduce electricity consumption and related internal heat gain. This can reduce the cooling load in the cooling season but increase the heating load in the heating season. As a result, they reduce CO_2 emissions in the spring and fall when cooling is still needed and electricity comes from fossil fuel, and they increase CO_2 emissions when natural gas is used for heating; and (6) by reducing the solar heat gain and increasing insulation, WINDOW reduces the cooling load but increases the heating load. Therefore, it reduces CO_2 emissions in the spring and fall, and increases CO_2 emissions when heating is needed.



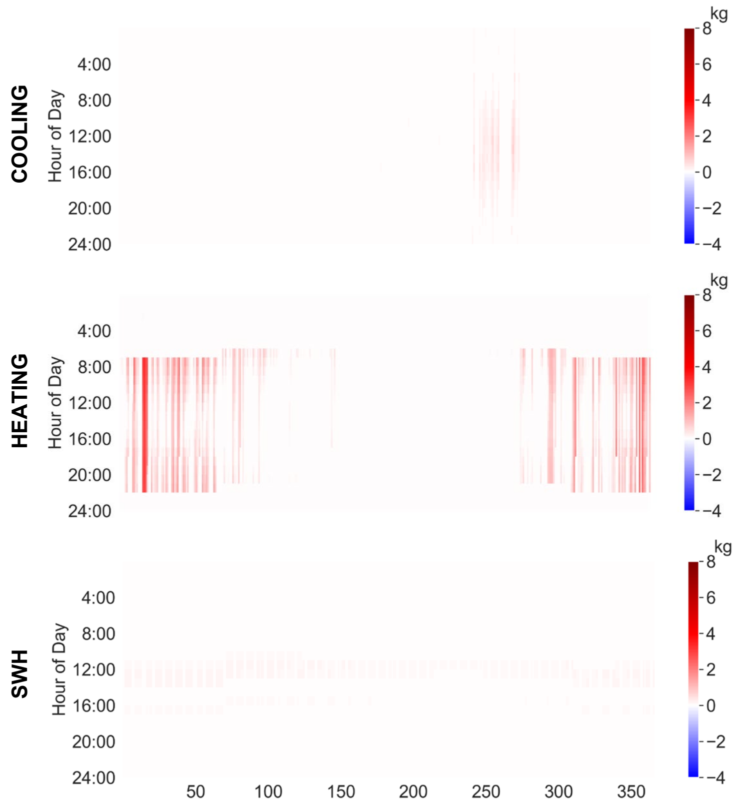
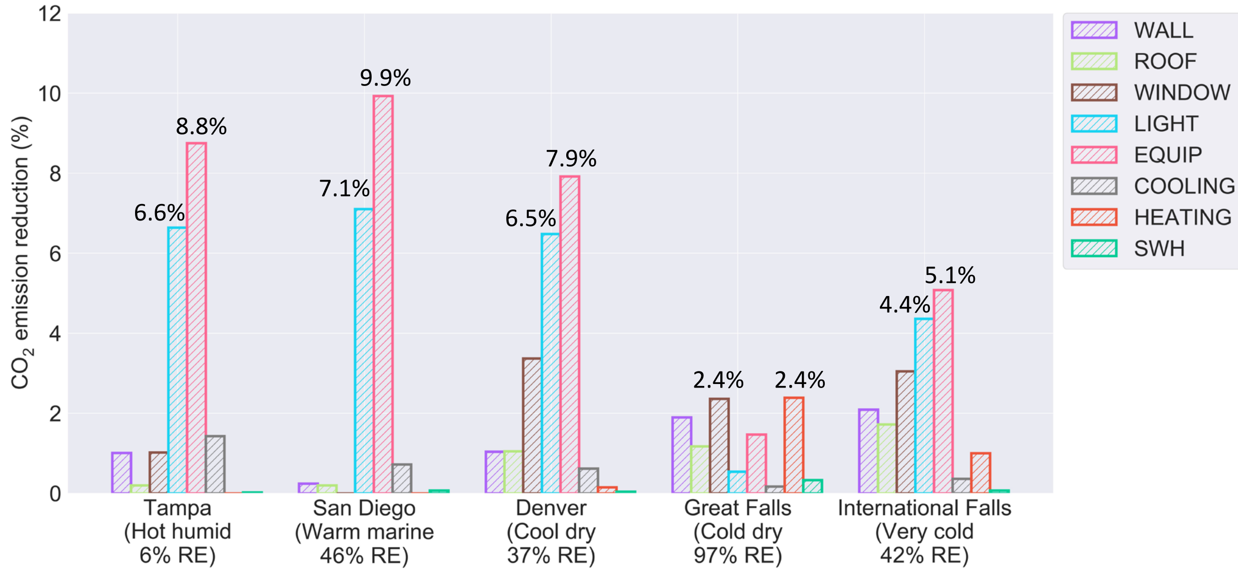


Fig. 10. CO_2 emission reduction by applying individual measures in Great Falls

The relative reduction of each measure is calculated using the CO_2 emission reduction effect (R_i) defined in equation (*1*). The results are shown in Fig. 11. The difference of R_i is small in cold locations (within 2.4% for Great Falls and within 5.1% for International Falls). The difference of R_i is relatively large in the other three locations (from 7.9% in Denver to 9.9% in San Diego) since EQUIP and LIGHT have significant impacts on R_i. The reason for this phenomenon is explained in Section 4. The EQUIP and LIGHT are the top two emission efficient measures in four locations except Great Falls where the top two are HEATING and WINDOWS.



Note: Renewable energy (RE) penetration is obtained from [31].

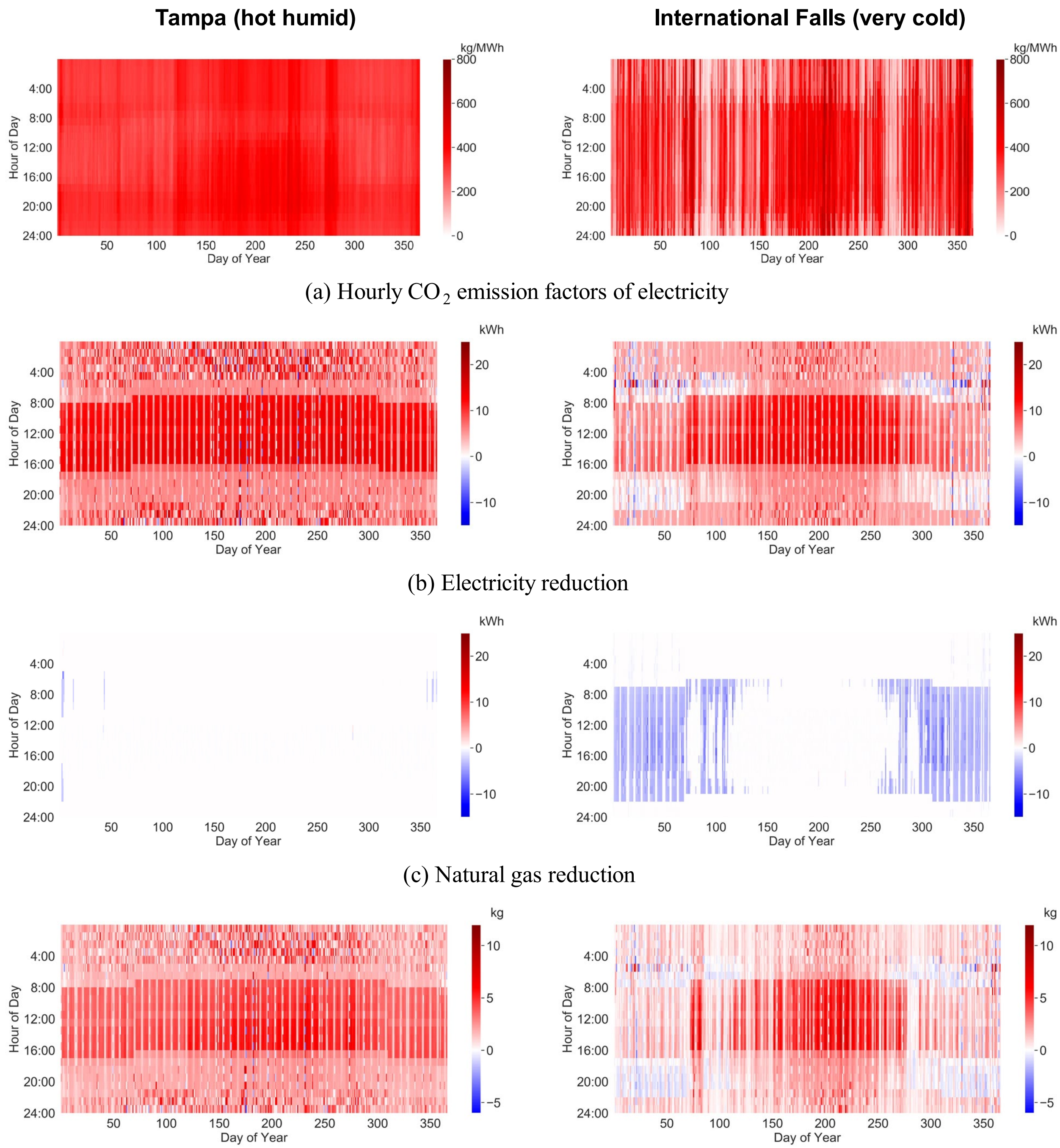
Fig. 11. CO_2 emission reduction effect (R_i) by applying individual measures

4. Discussion

4.1. Impact of climates on CO_2 emission reduction

In cold climates, improving lighting efficiency and improving equipment efficiency are less effective in emission reduction than hot climates. Fig. 11 shows that the CO_2 emission reduction effects of LIGHT and EQUIP in International Falls (cold climate) are 4.4% and 5.1% respectively, while they are 6.6% and 8.8% respectively in Tampa (hot climate).

Using EQUIP as an example, Fig. 12. shows the hourly CO_2 emission factors of electricity, the reduction of electricity consumption, the reduction of natural gas consumption, and the reduction of CO_2 emissions in Tampa and International Falls. Both locations have similar emission factors in electricity generation (Fig. 12 a). However, the reduction of electricity consumption by applying EQUIP is more effective in hot climates, such as Tampa (Fig. 12 b), since it also reduces the cooling load due to the reduced internal heat gain from the equipment. For cold climates, like International Falls, additional heating will be needed when internal heat gain resulted from equipment is reduced. This also leads to an increase of gas consumption in the cold climate location, as shown in Fig. 12 (c). As a combined effect, Fig. 12 (d) shows larger emission reduction resulted by improving efficiency of equipment in Tampa than International Falls.



(a) Hourly CO_2 emission factors of electricity

(b) Electricity reduction

(c) Natural gas reduction

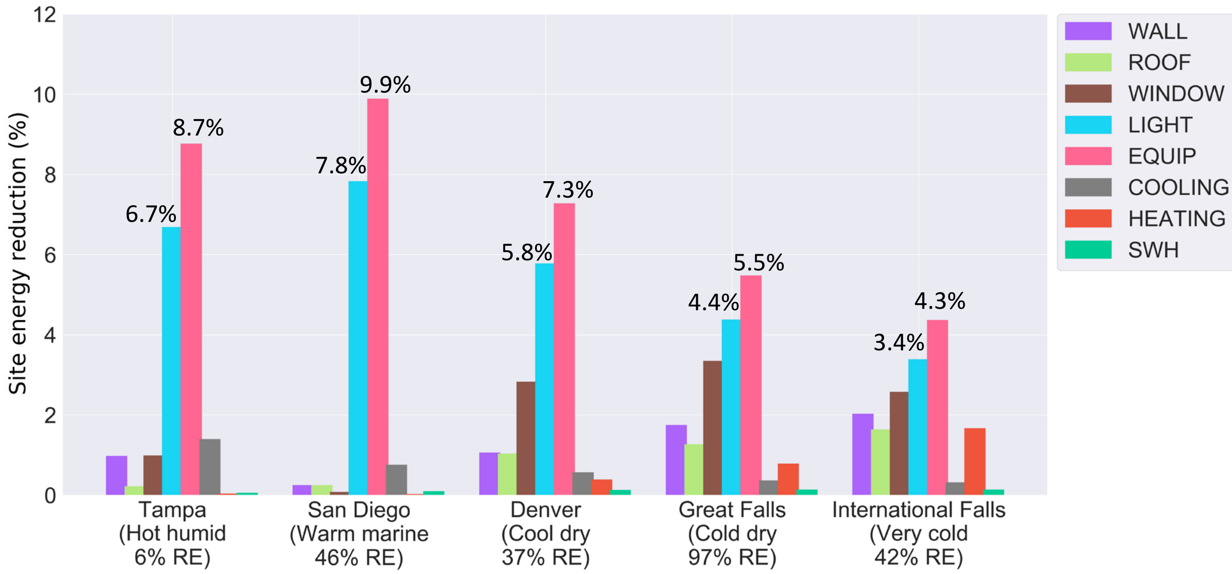
(d) CO_2 emission reduction

Fig. 12. Energy and CO_2 emission reduction by applying EQUIP in hot and cold locations

4.2. Measures to reduce energy and emissions

Due to the variability of CO_2 emission factors, the most energy efficient measure is not necessarily the most efficient emission measure. For instance, the most energy efficient measure in Great Falls is EQUIP (Fig. 13) while the most efficient emission measure is HEATING (Fig. 11). Improving equipment efficiency reduces electricity consumption and related internal heat gain. This can reduce cooling loads but increase heating loads. Therefore, improving equipment efficiency in Great Falls mainly reduces electricity consumption in summer. However, this large energy reduction does not lead to corresponding emission reduction because electricity in Great Falls in summer mainly comes from hydropower with zero emissions. On the contrary, natural gas is used for heating in Great Falls, improving heating efficiency can directly reduce emissions so that it becomes the most efficient emission measure.

A different example is San Diego, whose most efficient emission measure is the same as the most energy efficient measure: EQUIP, as shown in Fig. 11 and Fig. 13. There are two reasons. First, San Diego has little heating needs. Therefore, the emission reduction effect of HEATING is minimal. Second, only 46% of electricity comes from renewable energy. As a comparison, Great Falls gets 97% of its electricity from renewable energy. Thus, reducing electricity consumption by adopting efficient equipment can still lead to a good amount of emission reduction in San Diego.



Note: Renewable energy (RE) penetration is obtained from [31].

Fig. 13. Site energy reduction by applying individual measures

If a location doesn't have high renewable energy penetration of electricity generation, it is suggested to select energy efficient measures for emission reduction because emission efficient measures are same as energy efficient measures. For example, improving the efficiency of electric equipment and lighting are suggested retrofit measures. If a location has high renewable energy penetration of electricity generation, it is suggested to select retrofit measures that can reduce fossil fuel consumption for emission reduction. For example, improving heating efficiency is a suggested retrofit measure for buildings that natural gas is used for heating.

4.3. Impact of using hourly CO_2 emission factor

By comparing the CO_2 emission reduction difference between using our method and the existing method (adopting constant annual factor on the current year grid emissions), we find that estimating CO_2 emission reduction with the constant annual emission factor will overestimate or underestimate the reduction. Fig. 14 shows the estimation bias on emission reductions using the constant emission factor by comparing with the one using hourly factors.

Note: Renewable energy (RE) penetration is obtained from [31].

Fig. 14. Estimation bias on CO_2 emission reduction using the annual emission factor

To quantitatively compare the difference of emission reduction by using hourly emission factors and constant emission factor, Table 4 shows the CO_2 emission reduction by using these two methods and their difference. Fig. 14 and Table 4 shows that using the constant emission factor tends to overestimate the emission reduction in San Diego (up to 1550 kg), underestimate in Denver (up to 692 kg) and International Falls (up to 1165 kg), both over- or underestimating in Tampa and Great Falls. The largest difference occurs in San Diego and the smallest difference in Tampa.

Table 4. CO_2 emission reduction by using hourly emission factors and a constant emission factor

Location	Retrofit Measures	Emission Reduction using Hourly Emission Factors (kg)	Emission Reduction using A Constant Emission Factor (kg)	Emission Reduction Difference (kg)
Tampa	WALL	2618	2490	-128
	ROOF	525	495	-30
	WINDOW	2647	2521	-126
	LIGHT	17252	17404	152
	EQUIP	22739	22853	114
	COOLING	3717	3591	-126
	HEATING	8	8	0
	SWH	48	48	0
San Diego	WALL	265	271	6
	ROOF	219	262	43
	WINDOW	0	-57	-57
	LIGHT	7919	9469	1550

Location	Retrofit Measures	Emission Reduction using Hourly Emission Factors (kg)	Emission Reduction using A Constant Emission Factor (kg)	Emission Reduction Difference (kg)
	EQUIP	11066	11965	899
	COOLING	802	890	88
	HEATING	1	2	1
	SWH	82	82	0
Denver	WALL	3110	3107	-3
	ROOF	3136	3105	-31
	WINDOW	10126	9918	-208
	LIGHT	19457	18765	-692
	EQUIP	23753	23161	-592
	COOLING	1851	1667	-184
	HEATING	438	438	0
	SWH	123	123	0
Great Falls	WALL	801	539	-262
	ROOF	493	343	-150
	WINDOW	998	523	-475
	LIGHT	228	292	64
	EQUIP	622	772	150
	COOLING	72	97	25
	HEATING	1010	1010	0
	SWH	141	141	0
International Falls	WALL	5103	4862	-241
	ROOF	4200	3993	-207
	WINDOW	7421	6952	-469
	LIGHT	10631	9466	-1165
	EQUIP	12381	11728	-653
	COOLING	872	710	-162
	HEATING	2443	2443	0
	SWH	166	166	0

As shown in Fig. 2, San Diego has plenty of solar power during the daytime, thus, hourly CO_2 emission factors during daytime are lower than both the hourly emission factors during nighttime and the annual factor (Fig. 5). This will lead to an overestimated emission for energy used in the daytime if the annual factor is adopted. As a result, it will also overestimate the emission reduction for the proposed energy efficiency measures since they mainly reduce energy consumption in the daytime.

On the contrary, hourly emission factors in Denver and International Falls during daytime are higher than both the hourly emission factors at nighttime and the annual factors (Fig. *5*). Since electricity consumption mainly occurs during the day, applying annual emission factors to the reduced electricity consumption will underestimate the CO_2 emission reduction.

As shown in Fig. 2, Tampa's electricity source is dominated by natural gas (78%) and nuclear (12%), which leads to relative constant hourly emission factors (Fig. 5). Thus, using hourly or annual emission factors only results in a relatively small difference in the predicted emission reduction.

Although estimating CO_2 emission reduction with the constant annual emission factor can produce biases, it takes less time for data collection and processing. The existing method (adopting annual factor) is still applicable for locations where fossil fuel is dominated because using constant annual emission factor in these locations only produce minor biases. However, our proposed method (adopting hourly factors) is suggested for locations where renewable energy is dominated because using constant annual emission factor in these locations leads to large biases.

5. Conclusion

This study analyzed the CO_2 emission reduction of building retrofit measures that related to envelope and mechanical systems in five locations: Tampa, San Diego, Denver, Great Falls, and International Falls. Instead of using the constant annual CO_2 emission factor of electricity, this study adopted hourly emission factors. We found that using the constant emission factor cause estimation bias: it overestimates the emission reduction for most measures in San Diego, while it underestimates the reduction for most measures in Denver and International Falls. Another finding is that the same retrofit measure may have different CO_2 emission reduction depending on the climates: improving lighting and equipment efficiency has less impact on CO_2 emission reduction in cold climates than hot climates. Furthermore, the most energy efficient measure is not necessarily the most efficient emission measure: in Great Falls, the most energy efficient measure is improving equipment efficiency, but the most efficient emission measure is improving heating efficiency. Those finding are applicable only for medium office that natural gas is used for heating and electricity is used for cooling.

The innovation and contribution of this study mainly lie in the following two aspects. Firstly, it reveals that hourly emission factors should be adopted in CO_2 emission reduction analysis for locations where renewable energy is dominated. Secondly, the method of estimating CO_2 emission reduction of building retrofit measures proposed in Section 2.3 can be applied to other building retrofit cases. Using this workflow, future studies can estimate their CO_2 emission reductions by providing electricity emission factors together with their estimated building energy consumptions and retrofit measures.

This study analyzes the CO_2 emission reduction effect of building retrofit measures based on one-year simulation data. However, the composition of electricity generation may change over time, and CO_2 emission factors will change accordingly. Thus, if a building retrofit measure reduces electricity consumption, emission reduction resulting from it may change over time. With the increased penetration of renewable energy in electricity generation, the annual reduction of emissions due to the building retrofits will likely decrease. Since the effects of building retrofit measures will last for a few decades, it would be interesting to study the CO_2 emission reduction effect of building retrofit measures over a longer time frame.

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