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Performance Comparison of Cool, Green, and Black Envelopes in the United States

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Abstract. As one of the primary sources of greenhouse gas emissions, buildings that need deep decarbonization and passive cooling methods such as cool and green envelopes were regarded as promising solutions. Since previous studies have not comprehensively compared the application of cool roofs, cool walls, green roofs, and green walls in different climate zones in the U.S., this paper aims to fill this gap. Through EnergyPlus 22.1.0 simulation by using the primary school building model from the Department of Energy (DOE), energy savings, cost savings, and emission savings resulting from cool and green envelopes in 9 thermal climate zones are presented. Findings suggest that cool envelopes are more cost-effective with all positive net present values ranging up to 44$/m2 from a 40-year life-cycle cost analysis. By contrast, those of green envelopes are all negative. However, green envelopes lead to more energy savings, therefore providing more environmental benefits. In cold climates, such as Fairbanks (8), green roofs and green walls lead to 1.8 kg/m2 and 8.3 kg/m2 of reduction in CO2 emissions, while cool roofs and cool walls result in 0.6 kg/m2 and 1.6 kg/m2 emission savings, respectively. The data also shows generally walls have greater impacts compared to roofs as they benefit multiple floors. By presenting the simulation results, this study will provide a reliable criterion that aids in the selection of some passive cooling methods for building managers in the U.S.

Keywords: Greenhouse gas, envelopes, energy saving simulations.

1. Introduction

Recently, natural events and human activities have played a vital role in greenhouse gas emissions. Heat is trapped in the atmosphere, as a result, contributing to a series of serious issues - global climate change [1]. In 2021, greenhouse gas emissions in the United States are 6,340 million metric tons of CO_2 equivalent, as shown by data from the United States Environmental Protection Agency (EPA). As one of the primary sources, gas use in commercial and residential buildings contributes to 13% of total emissions [2]. Therefore, deep decarbonization in this field is urgently needed.

To that end, since the building envelope, or the construction, determines how it will respond to outdoor conditions, improved envelope performance can lead to positive energy savings, reducing cooling and heating requirements, building's total energy use, and possible greenhouse gas emissions during the consumption, moving it closer toward the goal of decarbonization. One of the approaches to improve building envelope performance, is passive design methods are considered viable ways to reduce energy consumption [3]. Here, passive strategies, such as the application of green roofs (GRs), green walls (GWs), cool roofs (CRs), and cool walls (CWs), refer to all environmentally friendly approaches that reduce building energy use through investigations in local climate and changes in building construction [4].

The four methods all function through decreasing heat transferred to the building. To begin with, GRs are basically roofs covered by plants. In some cases, the construction of GRs includes: a waterproof barrier, a root barrier, a drainage layer, soil, and vegetation on the outside. Those components act in a way to reduce heat gain in summer while also preventing heat loss in winter [5]. As proven in a study conducted by Ercan et al. [6], GRs reduced cooling load by up to 57% and heating load by up to 20%. Having similarities with the above, GWs are known as vertical greenery systems (VGS), with vegetation either planted or held in building facades. It provides shading, insulation, and evapotranspiration effects that will lower heat gains through control of heat transfer to the building. In Dahayanake and Chow's simulation set in Hong Kong and Wuhan, VGS reduced a maximum of 26ºC in surface temperature of the exterior walls and 3% in annual cooling energy use. At the same time, however, GW increased the heating load in winter due to lowered heat gains. Compared to bare facades, GW resulted in an increase in heating energy demand of 0.06 kWh in Hong Kong and 0.07 kWh in Wuhan [7].

Contrasting with what "green" refers to, "cool" stands for white coating with high solar reflectance, either in the construction of roofs or walls. Gao et al. conducted a study in which they discovered that CRs yielded positive annual savings of 4.1–10.2 kWh/m^2 source energy, 1.0–3.5 kg/m^2 CO_2, 5.1–13.2 g/m^2 NO_x, and 9.4–32.6 g/m^2 SO_2 when substituting for an aged grey roof in four hot-summer climate cities' office buildings in China. Granted, high solar reflectance has a negative effect of preventing heat gains in winter. Thus, winter heating penalties outweighed cooling savings in regions with cool weather such as Harbin and Changchun, China [8]. Similar patterns also appear in studies of CWs. When simulating the effect of CWs in isolated buildings in all U.S. climate zones, Rosado and Levinson found that climate zones with small savings were generally colder and less sunny. CWs yielded positive annual savings in heating, ventilation, and air conditioning (HVAC) energy costs in all warm climates, from 1A (Miami, FL) through 4B (Albuquerque, NM), while reductions happened only in certain building categories and vintages in cold climates [9].

Previous studies often made comparisons between either roofs and walls of similar construction [9][10][11] or GRs and CRs [12][13] to provide guidelines for selection. In general, assuming all else equal, comparing the effectiveness of roofs and walls relies on the roof area to net wall area ratio. For instance, cooling savings and heating penalties would be greater for CWs compared to CRs when there is a low ratio [9]. The same results appear in studies comparing GRs and GWs. In multi-story buildings, where the roof area to net wall area ratio was low, 100% GR coverage only resulted in a high energy saving of 0.72% on the highest floor, decreasing to 0.6% on the second highest floor and 0.01% on the third. Consequently, Dahayanake and Chow concluded that in a multi-storey building with equal area of GR and GW, GW was more effective, providing benefits to multiple floors [11]. On the other hand, GRs and CRs, or white roofs, are compared in both economic and environmental perspectives. For the former, in a 50-year life-cycle cost analysis (LCCA), Sproul et al. found that white roofs provided a 50-year net savings (NS) of \$25/m^2 and GRs had a negative NS of \$71/m^2 relative to black roofs. CRs were also three times more effective in mitigating global warming, but GRs provided stormwater management due to vegetation planted [12].

In sum, these studies have given detailed analyses of the economic and environmental benefits of the four passive strategies, comparing and contrasting between two of the four: GRs and GWs [10][11], CRs and CWs [9], and GRs and CRs [12][13]. Nevertheless, a holistic review of the comparison of all four strategies is still lacking. In addition, previous research mainly focused on office and residential buildings [8][9][13][14], overlooking these technologies' effects on some commercial buildings. Therefore, the gaps should be filled to give a reliable and comprehensive criterion for the selection of suitable passive design methods.

To address the research gap, this paper will present a holistic comparison of the effects of GRs, GWs, CRs, and CWs on the DOE prototype primary school building model. EnergyPlus 22.1.0 was used to simulate total site energy savings of building's energy consumption in 9 different U.S. climate zones. Thus, this study will provide a reliable criterion and aid in the selection of passive design methods for building managers.

2. Methodology

2.1. Building Model

A primary school building model is constructed in EnergyPlus 22.1.0, based on a DOE 2012 prototype. Its building shape and total area, together with the heat transfer coefficient (U-value) and construction of each building surface are shown in Fig. 1 and Table 1 However, the U-value here is only one example built under Albuquerque's climate conditions. As the floor's U-value varies with the zone's location within the building, Table 1 can only represent that of the corner classrooms.

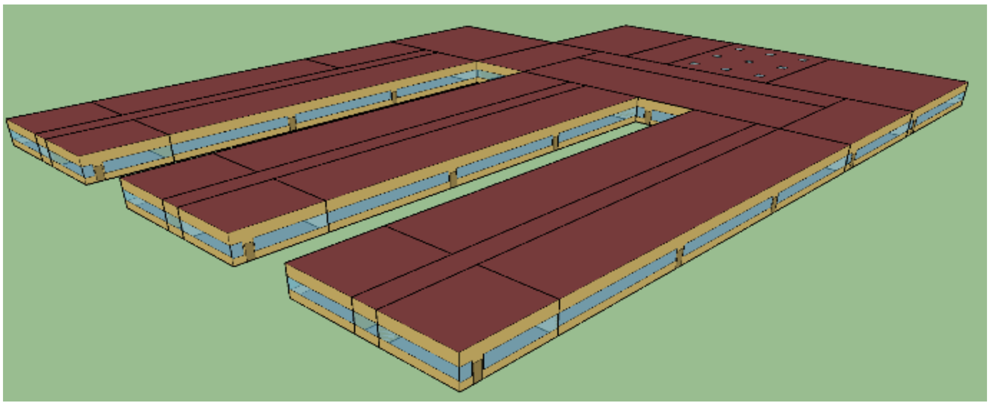


Fig. 1. Primary school building model.

Table 1. Building area and surface details.

Total Building Area (m^2)	6871.00	
Building Surface	**Construction**	**U-value ($W/m^2 \cdot K$)**
External Wall	F07 25mm stucco G01 16mm gypsum board Nonres_Exterior_Wall_insulation_grd G01 16mm gypsum board	0.943
Roof	F13 Built-up roofing Nonres_roof_insulation F08 Metal Surface	0.182
Floor	/	0.182

In addition, the infiltration is 2.15 cfm/m^2 for all zones. Internal heat gains vary with different occupancy densities, lighting power, and electric equipment. Hence, Fig. 2 and Fig. 3 show the contributions of each category to the total internal heat gains in thermal zones classrooms, and corridors during study periods. The HVAC system the model uses is package rooftop variable air volume (VAV) with reheat, with VAV as fan control, direct expansion as cooling type, and hot-water fossil fuel boiler as heating type.

9 climate zones of the United States are considered during the simulation, covered by 7 representative cities in different locations shown in Fig. 4, and the other two have representative cities Dubai and New Delhi.

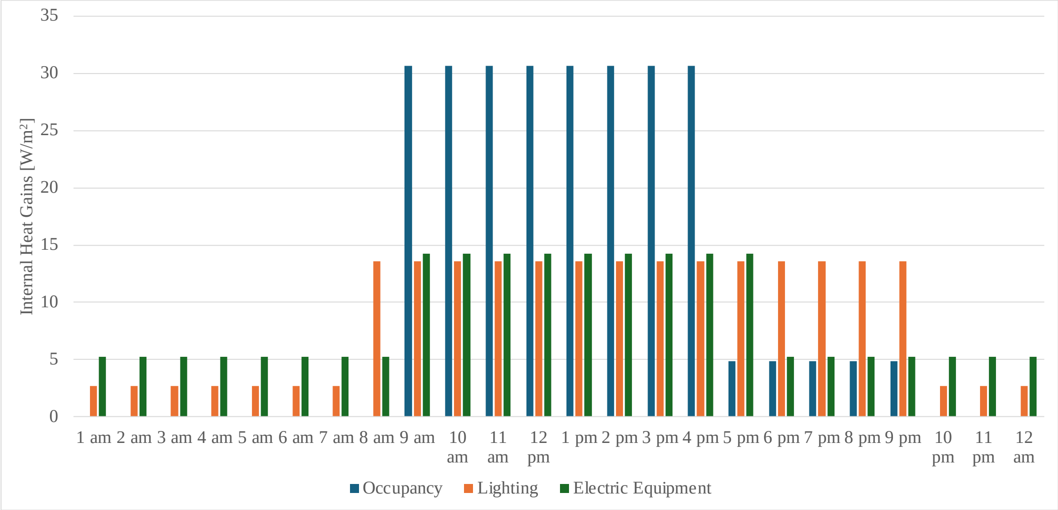


Fig. 2. Internal heat gains of classrooms (age 5-8) during study periods.

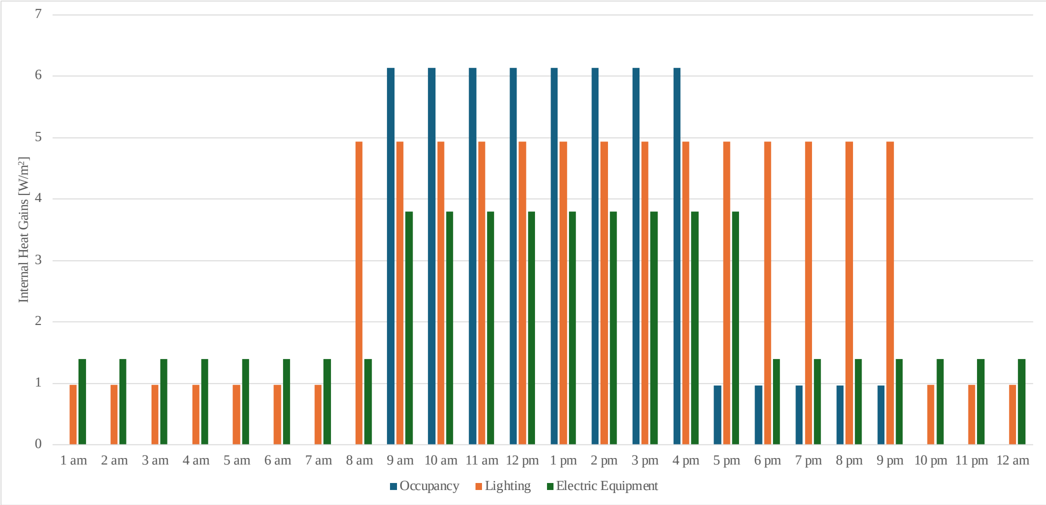
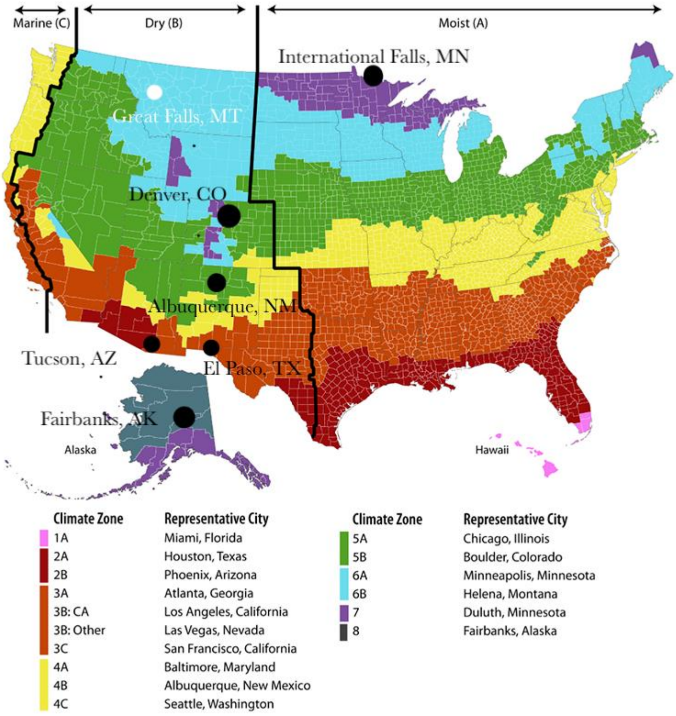


Fig. 3. Internal heat gains of corridors (school) during study periods.



Climate Zone	Representative City
1A	Miami, Florida
2A	Houston, Texas
2B	Phoenix, Arizona
3A	Atlanta, Georgia
3B: CA	Los Angeles, California
3B: Other	Las Vegas, Nevada
3C	San Francisco, California
4A	Baltimore, Maryland
4B	Albuquerque, New Mexico
4C	Seattle, Washington

Climate Zone	Representative City
5A	Chicago, Illinois
5B	Boulder, Colorado
6A	Minneapolis, Minnesota
6B	Helena, Montana
7	Duluth, Minnesota
8	Fairbanks, Alaska

Fig. 4. U.S. climate zones and the location of 9 cities [15].

2.2. The Setting of Cool Envelopes and Green Envelopes

This study simulates the effect of cool envelopes and green envelopes by changing or adding materials in their constructions, using the DOE 2012 prototype primary school building model. For CRs, the solar absorptance of the outer layer is changed to 0.2 to show the high solar reflectivity of the white coating, representing the albedo of the cool envelope as 0.8. For GRs, a green material, or roof vegetation, is added to the outer layer, with details shown in Table 2.

Table 2. Setting of green material in EnergyPlus model.

Height of Plants (m)	0.2
Leaf Area Index (-)	3
Leaf Reflectivity (-)	0.5
Leaf Emissivity (-)	0.95
Minimum Stomatal Resistance (s/m)	180
Soil Layer Name	Green Roof Soil
Roughness	MediumRough
Thickness (m)	0.2
Conductivity of Dry Soil (W/m·K)	0.35
Density of Dry Soil (kg/m^3)	1100
Specific Heat of Dry Soil (J/kg·K)	1200
Thermal Absorptance (-)	0.9
Solar Absorptance (-)	0.4
Visible Absorptance (-)	0.75
Saturation Volumetric Moisture Content of the Soil Layer (-)	0.3
Residual Volumetric Moisture Content of the Soil Layer (-)	0.01
Initial Volumetric Moisture Content of the Soil Layer (-)	0.1
Moisture Diffusion Calculation Method	Advanced

2.3. Life-cycle Cost Analysis (LCCA)

An LCCA model is constructed to compare the net savings of cool envelopes and green envelopes over a 40-year life cycle. As GRs and GWs are expected to last for at least 40 years while cool envelope life is 20 years, the replacement costs are only considered in the case of CRs and CWs [12]. Besides, the LCCA only accounts for the following parameters: installation, maintenance, and replacement, avoided power plant emissions (CO_2, NO_x, and SO_2), and storm-water-related benefits. Others such as heat island mitigation and biodiversity are not included. Table 3 shows default values used according to the study conducted by Sproul et al [12], in comparison to that of black envelopes, by assuming the costs of GWs are equal to GRs', and CWs' are equal to CRs'.

Table 3. Costs of cool envelope and green envelope in comparison with black envelope.

	GR	GW	CR/CW	Black
First installation cost ($/m^2)	172	172	22	22
Replacement cost ($/m^2)	0	0	22	22
Maintenance cost ($/m^2 year)	2.9	2.9	0.2	0.2
Peak load shaving benefit ($/m^2)	2.2	2.2	2.2	0
Annual stormwater fee ($/m^2 year)	0	0.9	0.9	0.9

Furthermore, in order to systematically compare the two, the net present value (NPV) of the 40-year life cycle cost savings is calculated by the following equation:

$$NPV = \sum_{i=1}^{40} \frac{(C_i - C_0)}{(1+r)^i} \tag{1}$$

where C_i is the annual profits of CRs or GRs compared to the grey envelope in $/(m^2·y); C_0 is the annual costs in $/(m^2·y), including installation, replacement, and maintenance costs and annual stormwater fee as shown in Table 2; *r* represents the real annual rate of return, with consideration of inflation, which is assumed to be 3% [13].

2.4. Heating and Cooling Site Energy Cost Savings

In this study, EnergyPlus simulation of GR's and CR's effects on the primary school building model over 9 climate zones in the United States is used to find total end-use site energy savings of natural gas and electricity results. Each is multiplied by the natural gas average commercial price and electricity average commercial retail price in U.S. 2022, which is 0.03869$/kWh and 0.1274$/kWh, respectively [16][17]. By summing up the products, total heating and cooling site energy cost savings are calculated using Eq. (2).

$$C = site\ N\ savings\ \times\ 0.03869 + site\ Y\ savings\ \times\ 0.1274 \tag{2}$$

where site natural gas savings (*N*) and site electricity savings (*Y*) are measured in kWh, and cost savings (*C*) are measured in dollars.

2.5. Power Plant Emission Savings

Power plant emissions refer to the pollution that comes with power generation. Energy savings the implementation of GRs and CRs result in can possibly lead to a decrease in power plant emissions [12]. In this study, CO_2, NO_x, and SO_2 emission reductions of the primary school prototype are calculated by Eq. (3).

$$M_i = \frac{E \times k_i}{\eta} \tag{3}$$

where M_i is the annual emission reduction of natural gas or electricity, measured in kg; E is the annual heating and cooling site energy savings of natural gas or electricity, respectively, in kWh; k_i is the emission coefficient as shown in Table 4, in kg/kWh; and η is the energy transmission efficiency (0.9 for electricity and 1.0 for natural gas) [13]. Here, an assumption is made that η is equal for natural gas and coal. The sum of the two M_i values is the total annual power plant emission savings.

Table 4. Emission coefficients of natural gas and electricity [18].

	CO_2 Emission Coefficient (kg/kWh)	NO_x Emission Coefficient (g/kWh)	SO_2 Emission Coefficient (g/kWh)
Electricity	0.429	0.65	2.7
Natural Gas	0.1805	0	0

3. Results and Discussion

3.1. Annual Site Energy Savings of Green Envelopes and Cool Envelopes

In this study, several DOE primary school prototype building models in representative cities of different U.S. climate zones are simulated using EnergyPlus 22.1.0, as shown in Table 5 [19].

Table 5. Thermal zones and representative cities.

Thermal Climate Zone Number	Thermal Climate Zone Name	Representative City
0B	Extremely Hot Dry	Dubai, United Arab Emirates
1B	Very Hot Dry	New Delhi, India
2B	Hot Dry	Tucson, AZ
3B	Warm Dry	El Paso, TX
4B	Mixed Dry	Albuquerque, NM
5B	Cool Dry	Denver, CO
6B	Cold Dry	Great Falls, MT
7	Very Cold	International Falls, MN
8	Subarctic/Arctic	Fairbanks, AK

As a result, site electricity and natural gas savings due to the implementation of CRs, CWs, GRs, and GWs in 9 representative cities are presented in Fig. 5, with the average, minimum, and maximum values shown in Table 6.

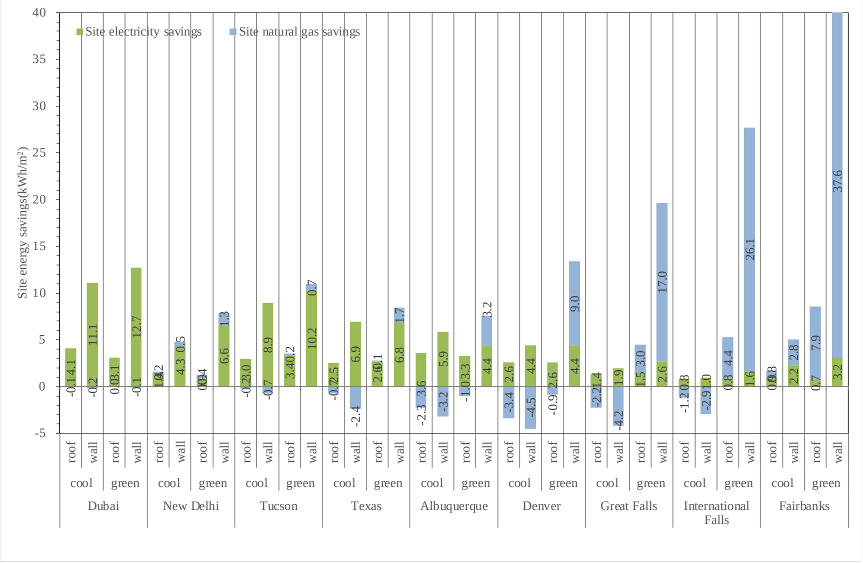


Fig. 5. Annual site energy savings of CRs, CWs, GRs, GWs.

Table 6. Statistic values of energy savings due to cool and green envelopes.

Type	Annual site electricity savings (kWh/m^2)			Annual site natural gas savings (kWh/m^2)		
	Average	Minimum	Maximum	Average	Minimum	Maximum
CR	2.5	0.8	4.1	-0.9	-3.4	0.8
CW	5.8	1.0	11.1	-1.5	-4.5	2.8
GR	2.2	0.7	3.4	1.4	-1.0	7.9
GW	6.5	1.7	12.7	9.6	-0.1	37.6

In general, the natural gas savings for GRs and GWs increases for different representative cities of thermal zone 0B to 8, from 0.0 kWh/m^2 and -0.1 kWh/m^2 per retrofit area in Dubai (0B) to 7.9 kWh/m^2 and 37.6 kWh/m^2 per retrofit area in Fairbanks (8). By contrast, the natural gas savings of CRs and CWs remain negative, with the slightly positive values in New Delhi (1B) and Fairbanks (8) being the outliers. Both can be explained by natural gas usage. It is mostly consumed to heat interior space and operate interior equipment and water systems. The savings increase for green envelopes due to the ability of the insulation layer in green materials to prevent heat extractions in winter. As a result, the heating load is decreased in cold climates, increasing natural gas savings. Hot climates, however, have little heating need, and less can be reduced. Thus, natural gas savings are the smallest in Dubai (0B) and the largest in Fairbanks (8). By contrast, high solar reflectivity materials used in CRs and CWs prevent the building from absorbing heat in winter, resulting in increased natural gas consumption.

On the other hand, site electricity savings for all four passive cooling methods generally show a decreasing trend along the axis. For instance, it decreases from 4.11 kWh/m^2 in Dubai (0B) to 0.93 kWh/m^2 in Fairbanks (8) for CRs and from 3.07 kWh/m^2 in Dubai (0B) to 0.73 kWh/m^2 in Fairbanks (8) for GRs. It is because they impact on-site electricity savings mostly through reducing cooling needs and the operation of fans. However, as the thermal zone changes from extremely hot dry (0B) to subarctic/arctic (8), there is less need for cooling and fans, and less can be reduced.

In addition, walls generally have a larger impact on energy savings compared to roofs. As primary schools are multiple-storey buildings, walls can affect multiple floors while roofs can only benefit the topmost floor [11]. The effect can be either positive or negative. In 5B Denver, CW’s site natural gas savings is -4.5 kWh/m^2 and CR’s is -3.4 kWh/m^2, while CW’s is 0.5 kWh/m^2 and CR’s is 0.2 kWh/m^2 in New Delhi (1B). This is also proven in the case of site electricity savings and green envelopes.

3.2. Annual Energy Cost Savings of Cool Envelopes and Green Envelopes

The cost savings of the four methods can be calculated through Eq. (2) and based on data in Fig. 5. Results are shown in Fig. 6.

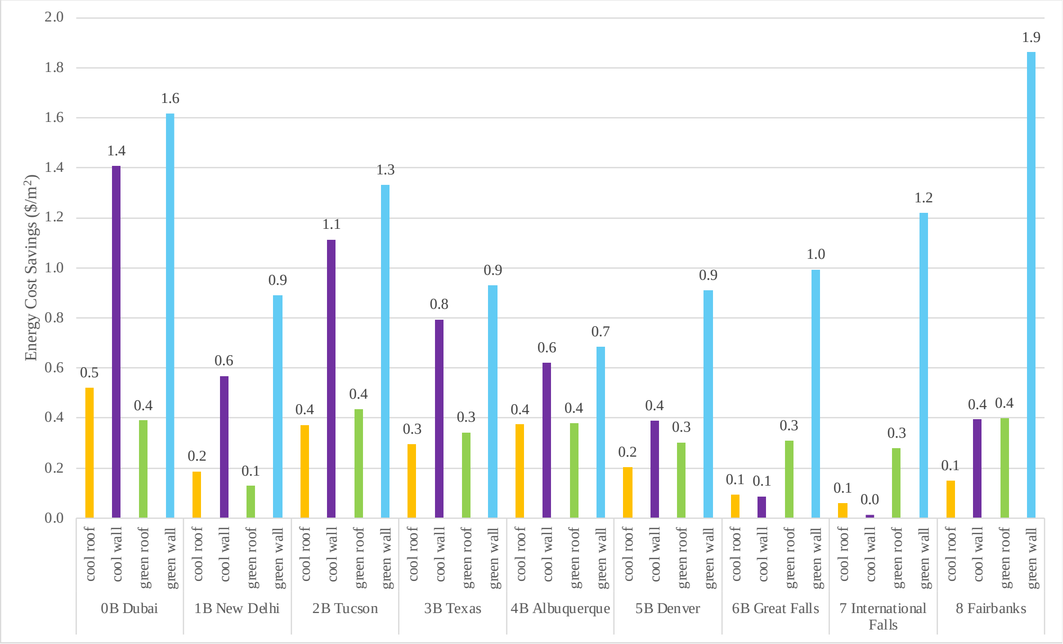


Fig. 6. Annual energy cost savings of cool and green envelopes in 9 thermal zones.

In general, the annual energy cost savings of cool and green envelopes are all non-negative. The implementation of cool walls has larger cost savings than cool roofs, which corresponds with the overall pattern of energy savings in Fig 5. For instance, CW's cost savings exceed CR's by 0.2 $\$/m^2$, and GW's exceed GR's by 0.3 $\$/m^2$ in Albuquerque (4B).

The cost savings for cool envelopes decreases when moving from 0.5 $\$/m^2$ and 1.4 $\$/m^2$ in Dubai (0B) to 0.1 $\$/m^2$ and 0.4 $\$/m^2$ in Fairbanks (8), with New Delhi (1B) and Fairbanks (8) being the outliers. It is due to the decrease in both site electricity and natural gas savings shown in Fig 5.

By contrast, the cost savings for GRs are mainly constant with a few fluctuations, while that of GWs decreases from 1.6 $\$/m^2$ in Dubai (0B) to 0.7 $\$/m^2$ in Albuquerque (4B), then increasing to 1.9 $\$/m^2$ in Fairbanks (8). This is because site electricity savings decreases from Dubai (0B) to Fairbanks (8), while natural gas savings increase. The increased amount is small compared to decreased electricity savings from 0B to 4B, with a ratio of 0.39, but is large from 5B to 8, equaling 23.8 times the decreased electricity savings, for GW. GR's CS is nearly constant, as a result, while GW's is decreased and then increased.

3.3. Net Present Value (NPV) of Cool and Green Envelopes

Concerning values in Table 3 and Eq. (1), the NPV of CRs, CWs, GRs, and GWs in 9 different representative cities are shown in Fig. 7.

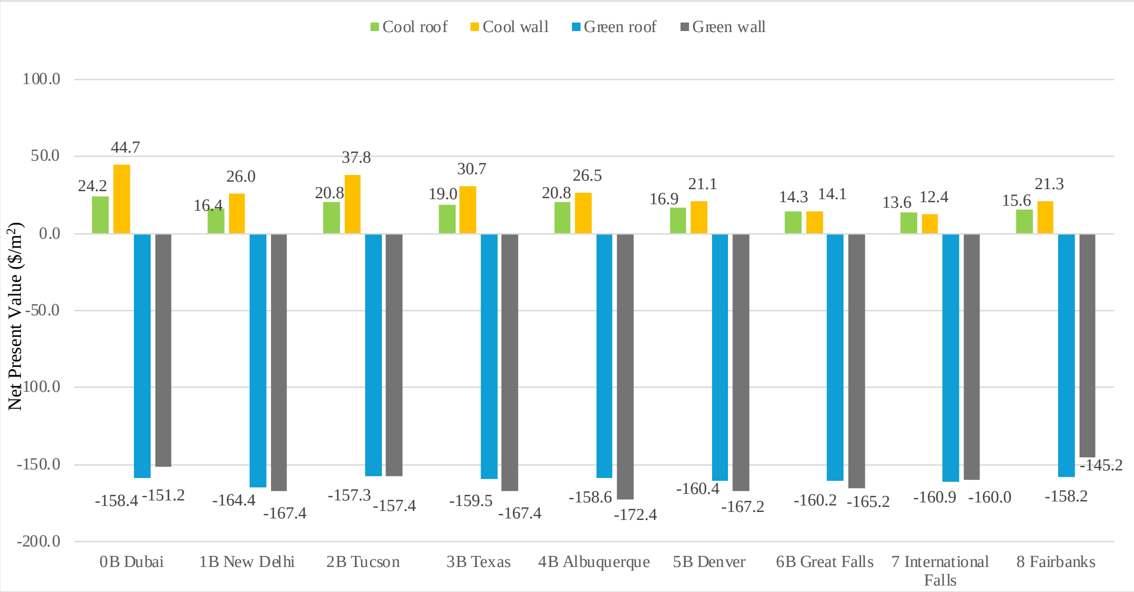


Fig 7. NPVs of cool envelopes and green envelopes compared to black envelopes.

NPVs of cool envelopes are all positive, ranging from 13.6 $\$/m^2$ to 24.2 $\$/m^2$ for CRs and from 12.4 $\$/m^2$ to 44.7 $\$/m^2$ for CWs. By contrast, the NPVs of green envelopes are all negative, varying from -164.4 $\$/m^2$ to -157.3 $\$/m^2$ for GRs and from -172.4 $\$/m^2$ to -145.2 $\$/m^2$ for GWs. It indicates that cool envelopes provide far more economic benefit compared to green envelopes due to lower first installation costs and maintenance costs. The difference is even more apparent in hot thermal zones as the implementation of high solar reflectivity materials decreases cooling costs significantly.

Here, CW's NPV is generally higher than CR's, with an average difference of 8.1 $\$/m^2$ due to higher energy savings, except in the case of Great Falls (6B) and International Falls (7). In comparison, GW's NPV is generally more negative than GR's though it contributes to more energy savings except in Dubai (0B), International Falls (7), and Fairbanks (8), with an average difference of 1.7 $\$/m^2$. However, it is reasonable since GW doesn't provide stormwater benefits, resulting in a 0.9 $\$/m^2$ annual stormwater fee while that of GR is zero.

3.4. Annual Emission Savings of CO2, NOx and SO2 of Cool and Green Envelopes

Through Eq. (3) and emission coefficients in Table 4, annual emission savings of CO_2, NO_x, and SO_2 are shown in Table 7.

Table 7. Annual emission reduction of CO_2, NO_x, and SO_2 of cool and green envelopes for representative cities.

City and the climate zone	Type		CO_2 emission reduction (kg/m²)	NO_x emission reduction (g/m²)	SO_2 emission reduction (g/m²)
Dubai (0B)	cool	roof	1.9	3.0	12.3
		wall	5.3	8.0	33.3
	green	roof	1.5	2.2	9.2
		wall	6.0	9.2	38.1
New Delhi (1B)	cool	roof	0.7	1.0	4.2
		wall	2.1	3.1	12.9
	green	roof	0.5	0.6	2.6
		wall	3.4	4.8	19.8

Tucson (2B)	cool	roof	1.4	2.2	8.9
		wall	4.1	6.5	26.8
	green	roof	1.6	2.4	10.1
		wall	5.0	7.4	30.7
Texas (3B)	cool	roof	1.1	1.8	7.6
		wall	2.9	5.0	20.8
	green	roof	1.3	1.9	7.9
		wall	3.5	4.9	20.4
Albuquerque (4B)	cool	roof	1.3	2.6	10.9
		wall	2.2	4.2	17.6
	green	roof	1.4	2.4	9.8
		wall	2.7	3.2	13.2
Denver (5B)	cool	roof	0.6	1.9	7.9
		wall	1.3	3.2	13.2
	green	roof	1.1	1.9	7.9
		wall	3.7	3.2	13.2
Great Falls (6B)	cool	roof	0.3	1.0	4.2
		wall	0.2	1.4	5.8
	green	roof	1.3	1.1	4.6
		wall	4.3	1.9	7.9
International Falls (7)	cool	roof	0.2	0.6	2.5
		wall	-0.1	0.7	2.9
	green	roof	1.2	0.6	2.5
		wall	5.5	1.2	4.9
Fairbanks (8)	cool	roof	0.6	0.7	2.8
		wall	1.6	1.6	6.7
	green	roof	1.8	0.5	2.2
		wall	8.3	2.3	9.6

The pattern of CO_2 emission reductions of cool and green envelopes is similar to that of energy savings. Cool envelopes' are generally lower than green envelopes' due to less energy savings, which also explains the difference between GW and GR, and CW and CR. From Dubai (0B) to Fairbanks (8), CO_2 emission reduction decreases for cool envelopes from 1.9 kg/m^2 and 5.3 kg/m^2 to 0.6 kg/m^2 and 1.6 kg/m^2, following the pattern of energy savings shown in Fig. 5. In comparison, the value decreases from 1.5 kg/m^2 and 6.0 kg/m^2 in Dubai (0B) to 1.4 kg/m^2 and 2.7 kg/m^2 in Albuquerque (4B) and then increases to 1.8 kg/m^2 and 8.3 kg/m^2 in Fairbanks (8) for green envelopes. It is because electricity savings, which contribute more to emission reduction with the coefficient 0.429 kg/kWh, decreases, and natural gas savings increase largely though with a smaller CO_2 emission coefficient of 0.1805 kg/kWh.

For NO_x and SO_2 emission reductions, both cool envelopes and green envelopes decrease from Dubai (0B) to Fairbanks (8), with New Delhi (1B) and Fairbanks (8) being the outliers. CR and CW decrease from 3.0 g/m^2 and 8.0 g/m^2 to 0.7 g/m^2 and 1.6 g/m^2 in NO_x emission reduction and from 12.3 g/m^2 and 33.3 g/m^2 to 2.8 g/m^2 and 6.7 g/m^2 in SO_2 emission reduction. Similarly, GR and GW decreases from 2.2 g/m^2 and 9.2 g/m^2 to 0.5 g/m^2 and 2.3 g/m^2 in NO_x emission reduction and from 9.2 g/m^2 and 38.1 g/m^2 to 2.2 g/m^2 and 9.6 g/m^2 in SO_2 emission reduction. The pattern is similar to that of site electricity savings as shown in Fig. 5, and it can be explained as natural gas savings lead to no NO_x and SO_2 savings, with the emission coefficient of 0 in Table 4. At the same time, walls usually contribute to more NO_x and SO_2 savings due to more site electricity savings.

4. Conclusion

In this study, an economic comparison of cool and green envelopes is made by simulating the effect of cool roofs (CRs), cool walls (CWs), green roofs (GRs) and green walls (GWs) on the DOE primary school model in 9 thermal zones (Extremely Hot Dry (0B), Very Hot Dry (1B), Hot Dry (2B), Warm Dry (3B), Mixed Dry (4B), Cool Dry (5B), Cold Dry (6B), Very Cold (7), and Subarctic/ Arctic (8)) of the United States, with EnergyPlus 22.1.0. It can be concluded that the choice among the four methods depends on the climate zone, first installation costs, maintenance costs, replacement costs and stormwater fees, and emission reductions. The study provides a reliable and comprehensive analysis, which eases building managers' burden in the selection of passive methods.

The findings of annual site energy savings indicate that green envelopes are generally better than cool envelopes at energy saving, with positive and increasing natural gas savings from 0.0 kWh/m2 and -0.1 kWh/m2 in Dubai (0B) to 7.9 kWh/m2 and 37.6 kWh/m2 in Fairbanks (8), except Dubai (0B), Albuquerque (4B) and Denver (5B). By contrast, natural gas savings of cool envelopes remain negative in 7 thermal zones, with New Delhi (1B) and Fairbanks (8) being the outliers. For green envelopes, GW results in more energy savings compared to GR, exceeding 9.5 kWh/m2 in Dubai (0B) and 32.2 kWh/m2 in Fairbanks (8) in total, for instance.

For cost savings due to site natural gas and electricity savings, the implementation of walls results in higher cost savings compared to roofs in all 9 thermal zones except International Falls (7), with an average difference of 0.8 $/m2 between GR and GW and 0.3 $/m2 between CR and CW. The results show that walls are more cost-effective when considering cost savings due to energy savings.

Though walls seem to save more costs, the NPV of the four methods after 40 years suggests differently. GW is more negative compared to GR, with an average difference of 1.7 $/m2, while CW's NPV value is higher than CR's on average by 8.1 $/m2. In general, green envelopes result in all negative NPV, while those of cool envelopes are all positive. It can therefore be concluded that cool envelopes are preferable in the aspect of the 40-year LCCA.

For reductions in CO2 emissions, cool envelopes decrease CO2 emission reduction from 1.9 kg/m2 and 5.3 kg/m2 to 0.6 kg/m2 and 1.6 kg/m2. In comparison, green envelopes decrease the value from 1.5 kg/m2 and 6.0 kg/m2 in Dubai (0B) to 1.4 kg/m2 and 2.7 kg/m2 in Albuquerque (4B) and then increase to 1.8 kg/m2 and 8.3 kg/m2 in Fairbanks (8) for green envelopes. It indicates that for colder climates such as Great Falls (6B), International Falls (7), and Fairbanks (8), GR and GW are better choices for more CO2 emission reduction. The pattern is similar for cool and green envelopes for NOx and SO2 savings, and walls lead to more reductions compared to roofs.

A conclusion is therefore reached that cool envelopes are preferable considering cost-effectiveness, while green envelopes are generally better in energy savings and emission reductions, therefore providing more environmental benefits to the society, including stormwater management, improvement in air quality, reductions in urban heat island effect, etc. This will also help building managers to meet DOE energy efficiency standards.

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