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Economic comparison of white, green, and black flat roofs in the United States

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ABSTRACT

White and “green” (vegetated) roofs have begun replacing conventional black (dark-colored) roofs to mitigate the adverse effects of dark impervious urban surfaces. This paper presents an economic perspective on roof color choice using a 50-year life-cycle cost analysis (LCCA). We find that relative to black roofs, white roofs provide a 50-year net savings (NS) of \$25/m^2 (\$2.40/ft^2) and green roofs have a negative NS of \$71/m^2 (\$6.60/ft^2). Despite lasting at least twice as long as white or black roofs, green roofs cannot compensate for their installation cost premium. However, while the 50-year NS of white roofs compared to green roofs is \$96/m^2 (\$8.90/ft^2), the annualized cost premium is just \$3.20/m^2-year (\$0.30/ft^2-year). This annual difference is sufficiently small that the choice between a white and green roof should be based on preferences of the building owner. Owners concerned with global warming should choose white roofs, which are three times more effective than green roofs at cooling the globe. Owners concerned with local environmental benefits should choose green roofs, which offer built-in stormwater management and a “natural” urban landscape esthetic. We strongly recommend building code policies that phase out dark-colored roofs in warm climates to protect against their adverse public health externalities.

1. Introduction

1.1. Background

Rapid urbanization in the United States (U.S.) during the 20th century converted much of the nation’s vegetation into urban areas, made up largely of buildings and pavements. According to the Statistical Abstract of the United States, nearly 75% of the U.S. population lives in large metropolitan areas [1]. In addition, U.S. buildings consume about 39% of total U.S. energy use, and contribute 40% of U.S. CO_2 emissions [2]. As global warming sets in, excess urban heat will exacerbate summer urban heat islands and lead to more heat-related deaths, respiratory illness, increased peak electricity use, and other ecologically adverse impacts.

These detrimental impacts of urbanization on society and the environment are partly attributable to the conventional use of black and dark-colored roofs on buildings throughout the U.S. The majority of the building sector in the U.S. is made up of impervious black or dark-colored roofs that absorb roughly 80% of incoming sunlight [3]. The sunlight that is absorbed heats the roof, which increases cooling costs in air-conditioned buildings, increases discomfort in unconditioned buildings, increases mortality during heat waves, and pollutes local and regional air. To mitigate the public health hazards associated with dark-colored roofs [4,5],[1] the construction industry has begun replacing them in recent years with two roofing alternatives—white and “green” (vegetated) roofs—that are much more beneficial to society and the urban environment.

Abbreviations: A/C, air-conditioning; BMP, best management practice; BUR, built-up bituminous roofing; CO_2, carbon dioxide; CSO, combined sewer overflow; GHG, greenhouse gas; GSA, General Services Administration; LBNL, Lawrence Berkeley National Laboratory; LCCA, life-cycle cost analysis; LID, low-impact development; NO_x, nitrogen oxides; NS, net savings; O&P, overhead & profit; SO_2, sulphur dioxide; SR, solar reflectance; TPO, thermoplastic elastomers; UV, ultra-violet; VOC, volatile organic compound.

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[1] Excess deaths during the 2003 European heat wave were estimated to be over 50,000 [4]; analysis of the 1995 Chicago heat wave identified as a critical risk factor living on the top floor of a building (beneath a black roof) [5].

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Table 1
Solar reflectance summary for white and green roofs.

		Aged white roof	Green roof
1	Solar reflectance (SR)	0.55	0.20
2	Ratio of SR (white/green)	2.75 (rounded to 3)	1
3	One-time emitted CO_2offset (tons CO_2e/100 m^2)	10	∼3
4	Row 3 converted to an annual rate over a 20-year roof service life (tons/year)	0.5	0.15
5	Global potential for cool roofs relative to black roofs, *one-time* CO_2offset (Gt)	24	8
6	Row 5 converted to annual rate over a 20 yr. roof service life (Gt/year)	1.2	0.4

As first estimated by Akbari et al. [6], converting 100 m^2 of dark roof to white offsets the emission of ∼10 tons of CO_2. Therefore, according to the (2.75 ± 0.5):1 ratio of the SR of white and green roofs, 100 m^2 of green roof has a one-time global warming offset potential of 3–4 tons of CO_2 equivalent.

1.2. White and green roofs are displacing black roofs

For flat "cool roofs," white is the most effective color. A white roof reflects 55–80%[2] of incident sunlight [3], keeping its surface cool on a clear summer day. This reduces heat transfer through the roof and makes the space below the roof more comfortable in unconditioned buildings. White roofs on air-conditioned buildings in hot climates can cut cooling energy use by 10–20% on the floor of the building immediately beneath the roof [6]. Cooler roof surfaces also mitigate the urban heat island effect, which improves air quality, reduces GHG emissions from power plants, and increases grid reliability during the summer (see supplementary data in the online version for more information on types of white roofs).

Moreover, increasing the solar reflectance (SR) of roof surfaces reduces the amount of heat absorbed at earth's surface and transferred into the atmosphere. This "albedo effect"[3] counters global warming; studies estimate that converting 100 m^2 (roughly 1000 ft^2) of dark roof to white offsets the emission of 10 tons of CO_2 equivalent over the lifetime of the roof [6,7]. Akbari et al. [6] also estimate the global cooling potential for cool roofs (mainly flat white roofs) in cities with hot summers to have a one-time offset potential of 24 Gt CO_2e. Assuming that the world's average car emits 4 tons of CO_2 per year, this offset is roughly equivalent to taking half of the world's approximately 600 million cars off the road for 20 years.

Relative to white roofs, green roofs are less reflective of incoming sunlight and therefore have lower global cooling potential. Figure 4 of Gaffin et al. [8] indicates that average July SR of an extensive green roof is 0.20. We assume that an aged white roof has an SR of 0.55, which can be rounded to three times the green roof SR owing to the uncertainty in both SR estimates. This threefold difference in solar reflectance corresponds to a threefold difference in global cooling potential, which is a distinction no studies have made to date. Applied to the above greenhouse gas offsetting estimates from Akbari et al. [6], this suggests that replacing 100 m^2 of dark roof with a green roof offsets the emission of 3–4 tons of CO_2 equivalent over the lifetime of the roof (see Table 1 for a comparison of global cooling potentials between white and green roofs). Thus white roofs, which offset 10 tons of CO_2 equivalent for every 100 m^2 of roof area, more effectively help to cool the world and mimic high-albedo land surfaces such as disappearing glaciers or Arctic sea ice[4] [9–11].

"Green" (vegetated) roofs vary in size, weight and vegetation, but they all shade the roof and protect it from water, UV damage, thermal cycling (expansion and contraction), and roof punctures. Vegetation and soil cool the roof's surface and the nearby air in two major ways: (1) they provide additional insulation and thermal mass to the roof, which reduces the transfer of heat into the space below; (2) evapotranspiration transforms sensible heat into latent heat of vaporization. However, it should be noted that while this lowers the city air temperature, it does not influence global temperatures.[5] On a sunny summer day, these factors reduce electricity use in air-conditioned buildings and improve comfort in non-air-conditioned buildings. By reducing electricity demand in cities, green roofs reduce the emission of air pollutants and GHGs from power plants, which in turn mitigates global warming and improves urban air quality.

Unlike white or black roofs, green roofs can be part of a building stormwater management plan. In wet weather, green roofs can reduce peak runoff by up to 65% and extend by 3 h the time it takes for water to leave a site. "Extensive" green roofs (described more in Section 1.3.2 and in detail in the supplementary data in the online version) intercept and retain the first 1–2 cm (0.5–0.8 in) of rainfall, preventing it from running off. In cities that require stormwater management plans, green roofs can save building owners money on both avoided stormwater fees and the costs of upgrading stormwater infrastructure [12]. This is particularly helpful in older cities that have undersized combined sewer systems.[6] Additionally, green roofs can create natural habitats, limit noise pollution, and increase property values.

Relative to black roofs that increase urban climate vulnerability, white and green roofs confer social benefits that make cities more comfortable. However, because there is no standard protocol for quantifying these urban heat island-related externalities, comparisons among these three roofing strategies are limited. To date there have been a number of published case studies that compare green roofs to black roofs [12–16] and white roofs to black roofs [17–20]. However, we could not find a comprehensive comparison of green and white roofs.

This paper presents a 50-year LCCA[7] for white, green, and black roofs using data collected from 22 flat roof projects or studies in the U.S. Even without accounting for important heat island-related externalities, we investigate whether white and green roofs offer purely economic advantages over black roofs. We seek to determine

[2] Reflectance degrades as the white roof ages—a solar reflectance of 0.80 is typical of a new white roof, and a solar reflectance of 0.55 is typical after 1–2 years.

[3] "Albedo" is a Greek term meaning "whiteness" and is used interchangeably with the term "solar reflectance."

[4] This analysis relies solely upon comparing differences in albedo, and does not consider the resulting changes in upward fluxes of sensible and latent heat [9,10]. Nor does it consider any climate feedbacks, such as cloud formation and precipitation, that can result from changes in roof albedo [11]. We take these to be second-order effects on which no consensus currently exists, but we acknowledge their ability to affect our results.

[5] Wind transfers cool moist air away from the city, where it condenses as rain. The heat released during condensation exactly cancels the evaporative cooling, so there is no net global cooling effect.

[6] These cities may experience CSOs (combined sewer overflow), which result in the discharge of untreated wastewater and stormwater from a combined sewer system directly into a river, stream, lake, or ocean.

[7] We refer to our analysis as an LCCA, whereas GSA [12] refers to its analysis as a cost-benefit analysis. We view these terms as interchangeable.

which roof type is most cost-effective over a 50-year life cycle, and we explore appropriate settings for each roofing strategy.

1.3. Roof installation, maintenance, and replacement costs[8]

1.3.1. White roof installation and end-of-service-life replacement costs

White roofs are a cost-effective alternative to black roofs on flat roof buildings because their installation costs are comparable, and in some cases cheaper. The most expensive TPO membrane is only $20/m^2 ($1.88/ft^2) including O&P, which is $7.40/m^2 ($0.69/ft^2) cheaper than installing the cheapest BUR, which costs $28/m^2 ($2.57/ft^2) including O&P [21].[9] For new and re-roofing commercial projects, the market share of asphalt-based roofs has dropped from its historical dominance to about 35% [22]. Furthermore, a study by Urban and Roth [23] showed that a white single-ply membrane now costs the same as a black single-ply membrane. We assume the first installation cost for white and black roofs to be equal at $22/m^2.

Disposal costs for a white or black roof depend on the condition of the roof; if the existing roof is a membrane or a BUR that is still in fair condition, it can be simply covered by a new membrane. In this case there are no disposal costs, only the costs of labor and the new membrane.[10] All roof lives are limited by three major natural forces: thawing/freezing, UV radiation, and daily thermal expansion/contraction. These latter two suggest that white membranes should have a longer service life than black membranes, and indeed there is much anecdotal evidence that they do; but actual measurements and statistics are lacking. This LCCA conservatively assumes that white and black membrane roofs have identical 20-year service lives.

1.3.2. Green roof installation and end-of-service-life replacement costs

Green roofs are typically more expensive to install than white or black. Peck and Kuhn [16] point out that even the cheapest category of green roof ("extensive" and inaccessible to the public) costs $108–248/m^2 ($10–23/ft^2), including 10% O&P, while an intensive and publicly accessible green roof costs $355–2368/m^2 ($33–220/ft^2), including the same 10% O&P. Due to the wide range of green roof costs, this LCCA only includes the least expensive category—extensive. We use $172/m^2 ($16/ft^2), the median installation cost of the 11 green roof projects surveyed in this report.

Because most of the green roof system components, e.g., growth media, sedum, etc., can be salvaged, the cost to replace an extensive green roof at the end of its service life is roughly 1/3 of the initial installation cost [12]. Thus we assume that the extensive green roof replacement cost is 1/3 the median installation cost, or $57/m^2 ($5.30/ft^2).

1.3.3. Black and white roof maintenance costs

Black and white roofs have similar maintenance needs that include various repair procedures (for punctures, leaks, etc.) as well as gutter and downspout cleanouts. The major difference in maintenance needs between black and white roofs is the issue of power washing to maintain high solar reflectance for white roofs. However, rather than including roof power washing in this LCCA, we assume that brand new white roofs are already weathered with an SR of only 0.55 (typical for an aged white roof).[11] Thus, the annual maintenance cost for black and white roofs is assumed to be the same at $0.20/m^2/year ($0.02/ft^2/year), which is the median maintenance cost of the 22 projects we surveyed.

1.3.4. Extensive green roof maintenance costs

The 40-year annual maintenance cost of an extensive green roof, including irrigation costs, is $2.90/m^2 ($0.27/ft^2) [12], which is 20 times higher than for black and white roofs. The greatest maintenance costs occur during the first two growing seasons (i.e., the establishment period), which are critical to ensure the system's long-term success. During this period, at least two laborers are required to perform a minimum of three visits per year [12]. However, after the establishment period, the demand for maintenance is reduced slightly.

2. Methodology

2.1. Life-cycle cost analysis (LCCA)

We use an LCCA to determine the net savings for green, white, and black roofs over a 50-year life cycle. Because green roofs are expected to last for at least 40 years (compared to 20 years for white and black roofs), a 50-year life cycle includes replacement costs for each of the three roof types analyzed in this study. The LCCA accounts for the following parameters: roof installation, replacement and maintenance, energy-related benefits (cooling/heating costs, A/C downsizing, peak shaving), avoided power plant emissions (CO_2, NO_x, and SO_2), equivalent CO_2 offset by global cooling (the "albedo effect"), and stormwater-related benefits (reduced fees and installation costs). Some other benefits of white or green roofs (relative to black roofs) are externalities that are either difficult to quantify or negligibly small, and are therefore NOT included in our LCCA. These include (among others) heat island mitigation, biodiversity, air quality, CO_2 sequestration, and increased property value.

Table 2 shows the lamentably sparse data collected from 22 case studies of building projects across the U.S. [13–15,17,24–34]. Many variables are regionally dependent, e.g., installation costs, water-for-irrigation costs, energy costs and demand, stormwater regulation/fees, roof size and accessibility. With only 22 case studies spread over seven ASHRAE Climate Zones [35], the data are clearly inadequate for regional LCCAs and we only use national median values.

We use Eq. (1) to calculate the net savings (NS) for each of three possible roof comparisons (xy = green–black, white–black, or white–green)[12]:

$$NS_{xy} = \sum_{t=0}^{N} \frac{S_{xy,t}(1+e_s)^t}{(1+d)^t} - \sum_{t=0}^{N} \frac{C_{xy,t}(1+e_c)^t}{(1+d)t} \qquad (1)$$

Here $S_{xy,t}$ represents the savings difference in year t between two roof types, $C_{xy,t}$ represents the cost difference in year t (including periodic replacement costs every 20 or 40 years), d is the intergenerational real discount rate (set to 3.0%), e_s and e_c are the annual fuel price escalation rates for the savings and costs respectively (averaging 0.4–2.6%) [36], and N is the number of years in the life

[8] Abbreviations and nomenclature for roof products discussed in this section can be found in more detail in the supplementary data (available in the online version at http://dx.doi.org/10.1016/j.enbuild.2013.11.058).

[9] The most expensive TPO is 60 mil. self-adhered. The least expensive BUR is asphalt base sheet, 3 plies #15 asphalt felt, mopped.

[10] This is the standard assumption we make in this study for product end-of-life condition.

[11] See supplementary data in the online version (http://dx.doi.org/10.1016/j.enbuild.2013.11.058) for an analysis that shows power washing for white roofs not to be cost-effective relative to leaving the roof in a less reflective condition.

[12] Note that although LCCA stands for life-cycle cost analysis, this report actually calculates and plots the net present value of savings (negative of costs), so the most desirable outcome is positive and not negative.

Table 2
Summary of 22 surveyed projects (key data and their medians).

#	Project	Location	Reroof	Year	Area (m^2)	First installation cost ($/$m^2$)			Maintenance cost ($/$m^2$/year)[$]			Heating savings relative to black ($/$m^2$/year)			Cooling savings relative to black ($/$m^2$/year)			Roof life (years)			Source
						G	W	B	G	W	B	G	W[#]	B	G	W	B	G	W	B	
1	Buchanan R-Mer Lite	Illinois	New	2008	1988	**172**	**99**	22	2.9	**0.2**	0.2	0.3		0.0	0.3	0.2	0.0	**25**	**30**	20	[24]
2	Buchanan White PVC	Illinois	New	2008	1988	**172**	**73**	22	2.9	**0.2**	0.2	0.3		0.0	0.3	0.2	0.0	**30**	**20**	20	[24]
3	Chicago City Hall	Chicago, IL	New	2001	1886	**215**	22	**129**	2.9	0.2	0.2	**0.7**		0.0	**0.3**	**0.2**	0.0	**40**	20	**20**	[25]
4	Forrestal combined	Washington, DC	New		4644	**226**	**31**	22	**0.5**	**1.1**	0.2	**0.7**		0.0	**0.4**	**0.4**	0.0	**30**	20	20	[26]
5	Niu et al. (9 projects)	Washington, DC	N/A	2008	1794	**210**	22	**242**	2.9	0.2	0.2	**0.0**		0.0	**0.3**	0.2	0.0	**40**	20	**20**	[15]
6	Fieldston	New York, NY	N/A	2007	8779	**183**	22	**75**	2.9	0.2	0.2	0.3		0.0	0.3	0.2	0.0	**30**	20	**20**	[27]
7	Walmart Chicago	Chicago, IL	New	2006	6968	**108**	**2.6**	22	**0.9**	**1.9**	0.2	0.3		0.0	**0.6**	0.2	0.0	**40**	**15**	20	[28]
8	Jefferson School	Alexandria, VA	Reroof	1994	7711	172	**42**	22	2.9	0.2	0.2	0.3		0.0	0.3	**4.0**	0.0	40	**20**	20	[29]
9	Tanyard	Athens, GA	N/A	2002	929	**155**	22	**84**	2.9	0.2	0.2	0.3		0.0	**0.4**	0.2	0.0	**40**	20	**20**	[14]
10	Our Savior's	Cocoa Beach, FL	Reroof	1995	1115	172	**5**	22	2.9	0.2	0.2	0.3		0.0	0.3	0.2	0.0	40	20	20	[30]
11	Portland Building	Portland, OR	New	2008	3716	**170**	22	**108**	**0.3**	0.2	**0.1**	**0.2**		0.0	**0.2**	0.2	0.0	**40**	20	**20**	[13]
12	Hamilton Apt. Building	Portland, OR	Reroof	1999	780	**164**	22	22	2.9	0.2	0.2	0.3		0.0	0.3	0.2	0.0	**40**	20	20	[31]
13	Multnomah	Portland, OR	Reroof	2003	1115	**162**	22	**108**	2.9	0.2	0.2	0.3		0.0	0.3	0.2	0.0	**40**	20	**20**	[32]
14	Large Retail Store	Austin, TX	Reroof	2000	9290	172	**16**	**16**	2.9	0.2	0.2	0.3		0.0	0.3	**0.6**	0.0	40	**13**	**13**	[17]
15	Kaiser Permanente	Davis, CA	Reroof	1997	2945	172	**22**	**22**	2.9	0.2	0.2	0.3		0.0	0.3	**0.7**	0.0	40	**20**	20	[17]
16	Kaiser Permanente	Gilroy, CA	Reroof	1996	2211	172	**22**	**22**	2.9	0.2	0.2	0.3		0.0	0.3	**0.4**	0.0	40	**20**	20	[17]
17	Longs Drugs	San Jose, CA	Reroof	1997	3056	172	**22**	**22**	2.9	0.2	0.2	0.3		0.0	0.3	**0.0**	0.0	40	**20**	20	[17]
18	Sacramento Office	Sacramento, CA	Reroof	1996	2285	172	**19**	**19**	2.9	0.2	0.2	0.3		0.0	0.3	**0.1**	0.0	40	**20**	20	[17]
19	Sacramento Museum	Sacramento, CA	Reroof	1997	455	172	**22**	**22**	2.9	0.2	0.2	0.3		0.0	0.3	**0.2**	0.0	40	**20**	20	[17]
20	Sacramento Hospice	Sacramento, CA	Reroof	1997	557	172	**14**	**13**	2.9	0.2	0.2	0.3		0.0	0.3	**0.2**	0.0	40	**20**	20	[17]
21	Scottsdale Insurance	Scottsdale, AZ	New	2008	1059	172	**86**	22	2.9	**0.2**	0.2	0.3		0.0	0.3	0.2	0.0	40	20	20	[33]
22	Con Edison	New York, NY	New	2008	1000	**172**	22	22	2.9	0.2	0.2	**0.3**		0.0	**0.2**	**0.1**	0.0	40	20	20	[34]
				MEDIAN VALUE		**172**	**22**	**22**				**0.3**		**0.0**	**0.3**	**0.2**	**0.0**	**40**	**20**	**20**	

Key: G, green; B, black, W, white; $, defaults from external sources rather than medians; #, no data on winter heating penalty for white.

cycle (50 years).[13] A positive NS indicates that roof color *x* is more cost-effective and a negative NS indicates that color *y* wins.

2.2. Data collection and handling sparse data

We calculate present values of the inputs of interest over a 50-year horizon. The values of these inputs are mainly extracted from 22 case studies of flat-roofed buildings across the U.S. (summarized in Table 2). The costs reported in case studies are printed in bold within Table 2; the bottom row reports medians of each column's bold values. However, because the available data are so sparse that not a single one of the 22 cases presents enough values to evaluate Eq. (1), we replace missing values with corresponding default values printed in italics. These default values are either medians of reported data or values gathered from relevant external sources regarding emission factors, air pollutant (CO_2, SO_2, NO_x) costs, stormwater infrastructure costs, and A/C equipment costs (default values are summarized in Table 3 [12,13,15,37–40]).

We can now apply Eq. (1) first to *each* of the 22 case studies (as in Fig. 1, discussed below, which compares the NS of white and green roofs). We can then use the same equation to compare default values (which are typically medians) in each roof color combination, as in Fig. 2, also discussed below.

3. Results

3.1. White roofs compared to green roofs

Fig. 1 displays the net savings of only "White–Green" comparisons. In nearly all of the 22 'White–Green' comparisons, the tall left stack reflects the fact that the white roof is much less expensive to install and maintain than the green roof. The shorter right stack shows the 50-year savings accrued by the green roof compared to the white roof, namely energy savings (cooling and heating), stormwater infrastructure and fee savings, and reduced power plant emissions. The difference of the left and right stacks is the total overall net savings of 'White–Green' over a 50-year life cycle (indicated by the blank space beneath each project's smaller stack in Fig. 1).

The median net savings of the 22 roof projects is \$102/m^2 (\$9.5/ft^2) in favor of white roofs, shown as a gold bar on the far right hand side of the figure.[14] The left-most project (#7) results in negative net saving values, meaning that a white roof is less cost-effective than a green roof for that project. For the remaining 21 projects however, white roofs are more cost-effective than green roofs, as pure roof costs (installation, maintenance, and, replacement) exceed the monetized environmental benefits of green roofs. It is important to note that we used one or more default values (shown in Table 3) in each of the 22 projects, so results would change as more real project cost and benefit data were included.

Fig. 2 takes a different approach; this figure uses the default values of Table 3 as generic proxies for all 22 project evaluations.[15] Fig. 2 illustrates that the generic white roof, compared to the generic green roof, has a NS of \$96/m^2 (\$8.90/ft^2), which is comfortably close to the NS of \$102/m^2 (\$9.5/ft^2) shown on the far right of Fig. 1. This means that white roofs are more cost-effective than green roofs over a 50-year life cycle and that a comparison of their generic costs is a reasonable representation of data from the 22 surveyed studies.

[13] Prices and escalation rates for energy and avoided emission of CO_2 are adopted from Rushing et al. [36].

[14] Note that although the median, in contrast to the mean, is insensitive to outliers, the standard deviation of the median is highly sensitive to outliers.

[15] The error bars in Fig. 2 come from variation in the 22 individual LCCAs that were used in Fig. 1.

Table 3
Median value inputs.

	Green	White	Black	Remarks
Installation, replacement and maintenance				
First installation cost ($/m^2)	172	22	22	Median value from Table 2, including labor
Replacement cost ($/m^2)	57	22	22	Equal to installation cost for white and black, 1/3 of installation cost for green
Maintenance cost ($/m^2 year)	2.9[a]	0.2	0.2	Median value from Table 2; assumes black equals white
Roof life (years)	40	20	20	Median value from Table 2
Disposal cost ($/m^2)	1.3	0	0	One-time cost
Energy-related benefits (relative to black)				
Avoided heating fuel cost ($/m^2 year)	0.3	0[b]	0	Median value from Table 2
Avoided cooling electricity cost ($/m^2 year)	0.3	0.2	0	Median value from Table 2
Peak load shaving benefit ($/m^2)	2.2	2.2[c]	0	CMU/ABSIC [37]
Air-quality-related benefits (relative to black)				
Avoided CO_2 emission[d,e] (kg/m^2 year)	5.7	4.3	0	Estimated from energy saving data
Avoided NO_x emission[d,f] ($/m^2 year)	0.011	0.009	0	Estimated from energy saving data
Avoided SO_2 emission[d,f] ($/m^2 year)	0.013	0.011	0	Estimated from energy saving data
CO_2e offset by global cooling[e] (kg/m^2)	34	100	0	One-time
Stormwater-related benefits (relative to green)				
Annual stormwater fee ($/m^2 year)	0	0.9	0.9	Assumes white and black retain same amount of stormwater as green—impervious surface fee[g]
Annual stormwater BMP maintenance ($/m^2 year)	0	1.5	1.5	Median value [12]
Stormwater BMP equipment cost ($/m^2)	0	44.7	44.7	One-time/replacement

[a] The cost is spread across the 50 years; adopted from GSA [12].
[b] None of the 22 case studies provided data for the winter heating penalty, thus this figure likely overstates the net savings.
[c] Data available for green roof only. Same value was assumed for white roofs because the cost difference is insignificant.
[d] Emission factors for heating fuel from EPA [38]; emission factors for electricity from EPA [39].
[e] Price information for CO_2, increasing linearly from $0/tons in 2005 to $115/tons in 2060, from Fuller and Peterson [40].
[f] Price information for NO_x and SO_2 from Niu et al. [15].
[g] This assumption refers to case #11 (Portland Building) in which up to 35% of the stormwater fee can be waived by installing a green roof or another best management practice [13].

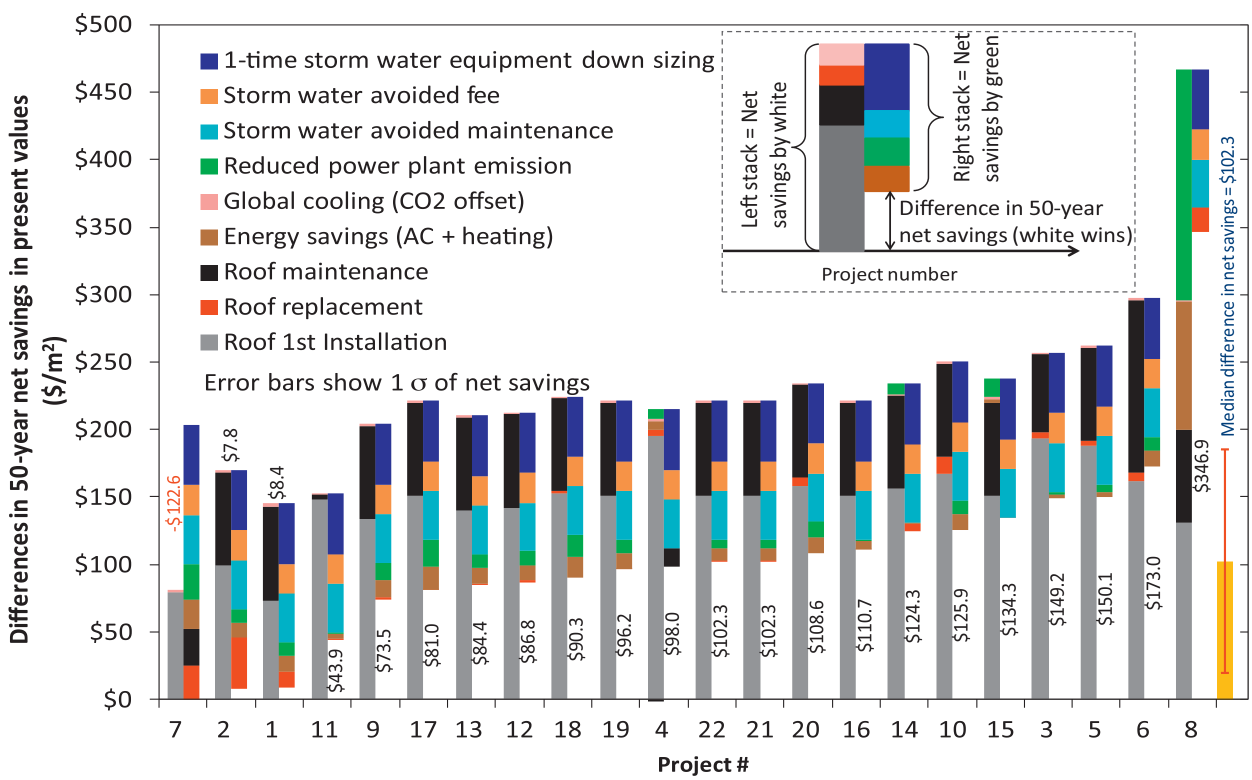
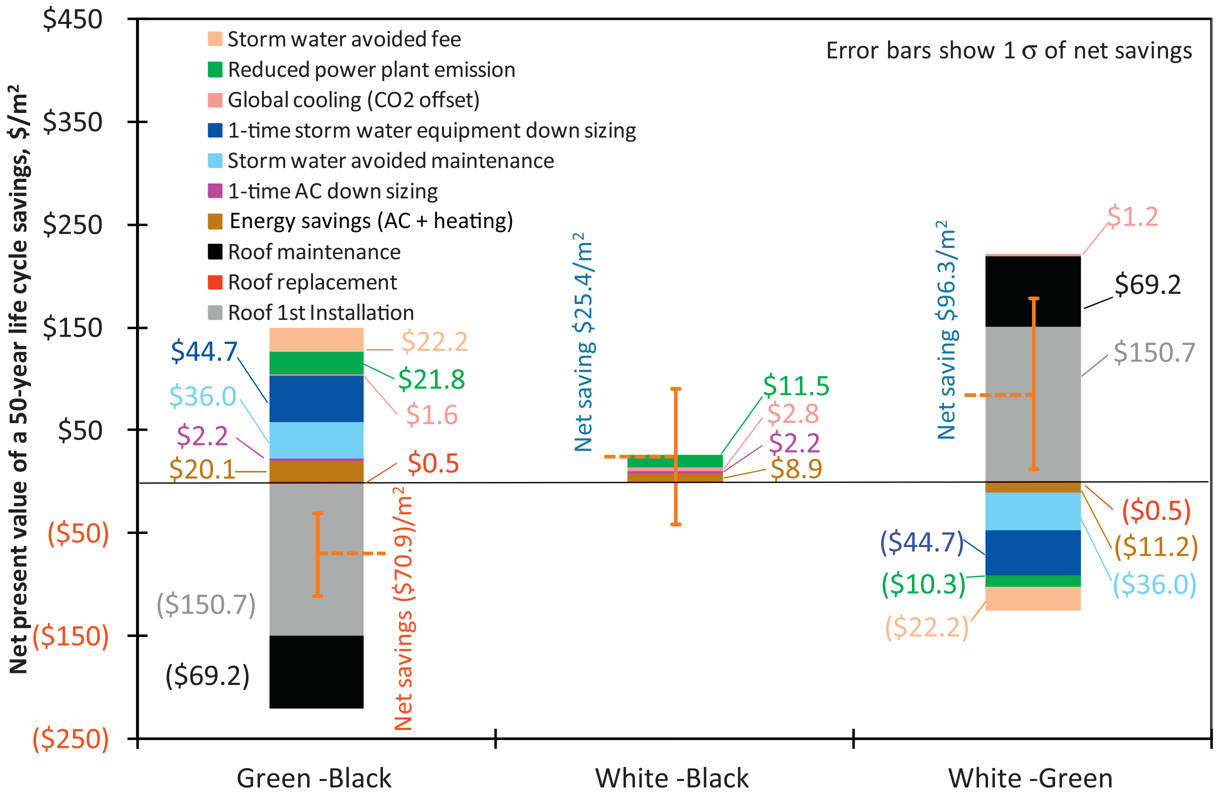


Fig. 1. Comparison of white and green roofs for each of the 22 surveyed projects.

3.1.1. Roof installation and replacement costs

The installation cost premium of green compared to white—$151/m^2 ($14/ft^2)—dominates the economics of the 50-year life-cycle NS of white and green roofs. The expensive installation cost of green roofs also contributes to their expensive replacement cost, despite the fact that green roofs last at least twice as long as white. However, since the majority of green roof components can be salvaged and only the waterproofing membrane needs to be replaced, the difference in roof replacement NS between white and green roofs is a more modest $35/m^2 ($3.25/ft^2)



The costs and benefits difference stack that has the highest NPV shows the roof type that is most cost-effective. For example, the "white – green" stack has a high NPV, meaning that white is more cost-effective than green. Parentheses around dollar values indicate negative values, thus the vertical scale turns negative below the zero line and thus in 'Green-Black' the net savings, ($70.90/m^2) indicates a negative net savings. Note that the gray column for green is dominated by its median first installation cost premium, $150.70/m^2.

Fig. 2. Net present value (NPV) of 50-year life cycle savings for three different roof color comparisons.

(see Table 3, Line 2).[16] Moreover, the 50-year maintenance costs of green roofs are $69/m^2 ($6.40/ft^2) more than those of white roofs owing to the need for additional maintenance for the vegetation. In this study, we only included the least costly type of green roofs (extensive), though the maintenance costs of green roofs can vary significantly according to the type of vegetation used.

3.1.2. Energy costs

Green roofs save roughly $11/m^2 ($1/ft^2) more than white roofs in energy costs because of the extra cooling effect of evapotranspiration during cooling seasons and the additional insulation of the growth medium during heating seasons. Depending on the climate, white roofs can lead to higher heating costs as a result of reduced solar heat gain, an effect referred to as the "winter heating penalty." This penalty varies sensitively from southern states to northern states (see "Map of Winter Heating Penalty by State" in [41]). The higher energy savings of green roofs is directly correlated to the larger reduction of power plant emissions (of NO_x, SO_2 and CO_2), giving them an additional savings of about $10.3/m^2 ($0.96/ft^2) compared to white roofs. The downsized A/C equipment savings were assumed to be the same for green and white roofs.

3.1.3. Global cooling

As discussed in Section 1.2, green roofs have less of a global cooling effect (in terms of CO_2 offsets) than white roofs, because green roofs have roughly one-third of the solar reflectance of white roofs. Surprisingly, this factor of three amounts to a relatively modest NS for white roofs of $1.20/m^2 ($0.10/ft^2), as shown in Fig. 2; this advantage contributes only roughly 1% of the total net benefit of white compared to green.

3.1.4. Stormwater-related costs

Savings from avoided stormwater-related costs (stormwater equipment downsizing, reduced stormwater maintenance and stormwater fee) are the major benefits of green roofs. The growth medium of the green roofs retains about half of the stormwater, which reduces the size of the residual stormwater management equipment (mainly cisterns) needed, particularly in cities that require a stormwater management plan for new buildings and major retrofits. The equipment downsizing results in a NS of about $45/m^2 ($4.20/ft^2). Additionally, the reduced maintenance costs associated with the stormwater equipment downsizing (mainly the maintenance of cisterns) results in another $36/m^2 ($3.30/ft^2) of NS (median value from GSA [12]). The extra stormwater retention capability of green roofs results in another $22.2/m^2 ($2/ft^2) of NS. We assumed that white and black roofs both paid the stormwater runoff fee of $0.90/m^2 year ($0.09/ft^2 year) as well as the costs of installing and maintaining a cistern or infiltration chamber. These additional costs absorbed by the white and black roofs result in an advantage for green roofs.

Taking into consideration all of the parameters discussed above, green roofs are about $96/m^2 ($8.90/ft^2) more costly than white roofs. The energy, air quality and stormwater benefits of green roofs add up to around $125/m^2 ($11.60/ft^2), a large portion of which is offset by the high extra costs of maintenance associated with green

[16] In year 40 the roof replacement NS is an insignificant $5.40/m^2 ($0.50/ft^2).

roofs over a 50-year period (an extra $69/m² ($6.40/ft²) compared to white roofs). However, the large first installation cost premium of green roofs remains the primary factor in its poor cost-effectiveness compared to white roofs.

3.2. Comparing all three roof colors

3.2.1. Green–black

As shown in Fig. 2, green roofs are less cost-effective than black roofs, while white roofs are more cost-effective than black roofs. The high installation and maintenance costs of green roofs outweigh the savings they offer and are the major drivers of green roofs' poor cost-effectiveness relative to black roofs. The total savings from green roofs of $149/m² ($14/ft²) are completely offset by their additional installation costs of $151/m² ($14/ft²). Roof replacement and maintenance for green roofs add $69/m² ($6.40/ft²) to the costs, leaving green roofs $71/m² ($6.60/ft²) more expensive than black roofs over a 50-year life cycle.

3.2.2. White–black

White roofs have the same low installation (and replacement) costs as black roofs. Thus, the savings from energy use, power plant emissions, and global cooling associated with white roofs lead to a NS of about $26/m² ($2.40/ft²) compared to black roofs over a 50-year life cycle. The maintenance costs were assumed the same for both white and black roofs.

4. Discussion

4.1. Choosing a roof color

Decision-makers face three primary options when choosing a roof color—white, green, or black. While black hot-mop roofs have been historically dominant for flat-roofed buildings, factory-produced roof coatings and membranes have largely taken over the U.S. roofing market in recent years. Since most of these products can be made white at no additional cost, the cost premium of white over black has virtually disappeared, and all of these technologies run from $10–30/m² ($1–3/ft²). Large corporations like Walmart, which owns hundreds of millions of square feet of roof space in the U.S., now choose white membrane roofs [42]. More recently, cities, states, government agencies and model building energy efficiency code organizations have implemented white roof requirements for new and replacement flat roofs on apartments and non-residential buildings.[17]

However, only a small fraction of cities and states in the U.S. are up-to-date in adopting these model standards including cool roofs. Accordingly, we recommend that every U.S. city and state as far north as Chicago, IL or Boston, MA implement a no-cost upgrade program for flat commercial building roofs to require white roofs for new construction and end-of-service-life roof replacements. This "no-cost upgrade program," as recommended by Levinson [43], shows that a 20-year phase-in campaign of white roofs on all commercial flat roofs in the U.S. could save more than one quadrillion BTUs in net primary energy (a present value of nearly $8 billion) at little or no extra up-front cost.[18] The projects we surveyed confirm this first-cost parity. The purely economic 50-year net savings of $25/m² ($2.40/ft²) in favor of white roofs, though only $1/m² year when annualized, is likely to underestimate of the true societal advantages of white roofs—namely, dark roofs pose a public health threat by exacerbating urban heat islands. We therefore recommend that architects and building owners choose white when deciding between white and black roofs.

Green roofs have also grown more popular in recent years, but our LCCA shows that green roofs are the least cost-effective of the three options studied, though only by a small margin on an annualized basis. Compared to green, white roofs offer a 50-year NS of $96/m² ($8.90/ft²) and black roofs offer a NS of $71/m² ($6.60/ft²) over the same period (see Fig. 2). When annualized over 50 years, however, these premiums for green are just $2–4/m² year ($0.20–0.40/ft² year). This annualized cost difference should not deter building owners who are relatively unconstrained by budget to opt for green roofs to capture their positive environmental qualities, heat island mitigation potential, and public health advantages—none of which are included in our LCCA.

4.2. Heat island mitigation and policy implications

As noted in Sections 1.1 and 1.2, white and green roofs offer local cooling benefits that can mitigate urban heat islands that have been partly caused by the prevalence of dark roofs. While we show black roofs to be more cost-effective than green roofs, and only slightly less cost-effective than white roofs, the factors included in our analysis are limited to those that can be monetized for the purposes of an economic comparison; choosing dark roofs in warm climates can exacerbate heat waves and risk human lives, which are not directly reflected in our LCCA. Conversely, choosing green roofs for their environmental or esthetic benefits, in spite of their poor cost-effectiveness, risks only money rather than human lives.

White roofs are the most cost-effective strategy, even without accounting for their heat island mitigation virtues. Still, the fact that the large public health advantages of green or white roofs over black roofs cannot be incorporated into an economic analysis indicates that private actors will not always make the socially optimal roofing choice. This presents a strong case for public policy to intervene by phasing out black roofs in locations with hot summers, as has been implemented in California [44], Chicago [45], New York [46], and several smaller cities.

5. Conclusion

We conclude that the choice of white vs. extensive green roof should be based on the environmental and societal concerns of the decision-maker. If *global warming* is a major concern, white roofs, which are around three times as effective at cooling the globe as green roofs, will be the preferred choice. On the other hand if the *local environment* is a primary interest, green roofs will be preferred. Of course, stormwater management may be a decisive factor in favor of green roofs, particularly in the presence of strict local stormwater regulations.

This study was intended to address the choice between the two principal types of environmentally friendly roofing strategies—that is, white vs. green—by providing the first empirical comparison between them that we are aware of. Our economic results over a 50-year life cycle were conclusive in favor of white roofs, but only over a sample of 22 projects that are fairly representative of various U.S. regions. Still, our lessons learned from this comparison teach us that each individual choice between white and green roofs depends

[17] See the Global Cool Cities Alliance's Cool Roofs and Pavements Toolkit (http://coolrooftoolkit.org) for a complete list of U.S. cool roof building codes and standards.

[18] These net primary energy and cost savings differ from, but are based on, those reported in Table 1 of Levinson [43], which assumes an unrealistically instantaneous phase-in of white roofs on flat-roofed buildings in all RECS U.S. climate zones. We adjust those results by scaling the annual values by $\sum_{i=1}^{20}(i/20)(1+r)^{-i}$ to determine results of a more realistic linear phase-in of white commercial roofs in all RECS U.S. climate zones over 20 years ($r = 0.03$).

heavily on case-by-case factors. Among these, summer rainfall patterns, climate, energy prices, and stormwater management fees and policies may greatly influence the results of the comparison. We therefore cannot present a simple conclusion for environmentally friendly roofing, but we do strongly recommend either option over dark roofs that increase building energy costs, summer urban heat islands, and global warming.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enbuild.2013.11.058.

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