Systematic Literature Review on Impact of Low slope vs. Steep Slope Roof Membrane Color on Energy Efficiency

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Abstract

A sustainable building envelope is important for building energy-efficient structures that contribute to sustainable communities. The current study compares the low slope versus steep slope roofing systems with varying solar reflectance and albedo factors to document the impact on energy efficiency via cooling/heating energy usage due to the roofing systems. A systematic literature review was conducted to compare the documented data from various literature sources with increasing solar reflectance and albedo scores and their impact on energy efficiency. The systematic literature review considered data from 65 papers to analyze parameters like solar reflectance and albedo for different types of roofs, identifying key limitations and gaps that pave the way for future study design on roofing systems. The study provides a useful tool to understand the impact of roof performance on energy efficiency and make informed decisions about implementing cool roofs.

Keywords

Cool Roof, Sustainability, Energy Efficiency, Albedo, Reflectance

1. Introduction

The United States of America has been ranked 41st out of 163 countries analyzed in the Sustainable Development Report 2022. This report highlights the importance of having a sustainable building envelope for sustainable cities and communities identified as an area of focus and improvement (Sustainable Development Report, 2022). The construction industry is the largest consumer of raw materials and produces waste material, which has negative impact on the environment. (UN Environment, 2017). For example, residential (steep-slope roofs) and commercial buildings (steep-slope and low-elope roofs) consume about 40% of the total energy usage in the USA. (Seiferlein et al., 2004)

The energy consumed during the operation and maintenance of buildings includes the energy needed for lighting, heating, cooling, and ventilation systems, as well as the energy consumed by electronic devices, appliances, and other equipment used in the building. Various strategies such as building insulation, efficient heating and cooling systems, and efficient building envelope such as use of efficient roof systems in building design can help reduce energy consumption. Roofs account for approximately 20%-25% of building surfaces in urban areas (Costanzo et al., 2016). Additionally, roof systems are critical to thermal performance of a building as it contributes up to 50% of the total thermal load of the building (Nahar et al., 2003). Some of the solutions include modifications on the roof's surface, such as changing the color or utilizing high reflective materials. (Boixo et al., 2012)

The current study looks back in time, collates the findings and analyzes the impact of changing albedo and solar reflectance on energy efficiency. The Solar Reflectance measures a roof's capacity to reflect solar energy back into the atmosphere (scale 0-100). Albedo is the proportion of incident radiation that is reflected from the surface of the roof (Dobos, 2005). The solar energy that is not reflected by the roof is absorbed, raising the temperature of the building. Albedo values vary from 0 to 1, with 0 being the darkest surface and 1 representing the lightest surface, absorbing 100% and 0% of solar radiation, respectively. The objective of the study is to conduct 1) a systematic literature review to document the effect of solar reflectance and albedo of roofing membrane on the energy efficiency of a building and 2) to organize the data and findings based on study design parameters to capture the changing efficiency over solar reflectance and albedo scores.

2. Methodology

This study examines the changing albedo and reflectance scores and its impact on energy efficiency for various roofing systems. SLR involves comprehensive search is conducted to identify relevant literature. This can include databases, journals, conference proceedings, and other sources. Further, this study synthesized and analyzed data collected from the literature and then summarized and organized into themes to facilitate the analysis. With various approaches to searching dedicated words and word associations in a literature review, such as narrative summary; content analysis; case, survey, and comparative analysis; this study identified literature with the defined keywords in the beginning and followed up with content and comparative analysis (Sharma et al., 2022). Various combinations of key words including, but not limited to 'cool roof', 'energy efficiency', 'albedo', 'reflectance' and 'insulation'. Table 1 shows the results of a search run on twelve (12) databases using a combination of the above-mentioned keywords.

Table 1: Search results and Database keywords

S. No.	Database	# of initial identification	# of inclusion criteria	Keywords
1	Engineering Village	178	12	"cool roof" AND "energy efficiency" "cool roof" AND "temperature" "cool roof" AND "albedo" "cool roof" AND "reflectance" "cool roof" AND "insulation"
2	ProQuest	287	3	
3	ACM Digital Library	1	0	
4	Web of Science	234	7	
5	Business Source Complete	20	2	
6	Academic Search Complete	97	10	
7	Berkeley Lab Heat Island Group	165	6	
8	Springer Link	172	2	
9	IEEE	32	1	
10	Wiley Online Library	71	2	
11	OSTI	121	5	
12	Clemson Libraries	313	15	
	Total	1691	65	

The keywords and their Boolean logic combinations (Yoshii et al., 2009) were searched for the initial identification of relevant publications across various databases (Sharma et al., 2022). This initial search retrieved 1,691 articles over the last 20 years. The inclusion criteria were (1) only peer-reviewed publications; (2) articles with data on various roofing systems and its impact on energy efficiency that measure cooling/heating energy usage, dollar savings, temperature reductions; (3) cases from all over the world; and (4) authenticity of the source. An overview of the process for selecting the relevant article is shown in Table 4.

Table 2: Selection of relevant articles

Steps	Results
Step 1	Initial identification based on keywords 1691 articles identified
Step 2	Narrowing down initial identification based on inclusion criteria, peer reviewed articles and study design 747 Articles selected
Step 3	Review of articles and abstract to identify articles relevant to the aims of this paper 325 Articles eligible
Step 4	Review of articles that quantify the effect of cool roof on energy efficiency 65 Articles included

The following factors were identified through an extensive literature review.

- Sample size of the roofs investigated, study location, climate, the color of the roof membrane (albedo and reflectance scores), low vs. steep slope, study limitations and conclusions.

The current scope includes, sample size of the roofs investigated for low vs. steep slope roofing systems. The goal of this stage is to identify patterns, trends, and relationships in the data, as well as to draw meaningful conclusions from the data. The data analysis process involves systematically reviewing the collected data, categorizing it in accordance with the established criteria, and identifying patterns and themes. In the end, the steering committee validated results.

3. Results and Discussion

The purpose of the systematic literature review was to analyze the impact of reflectance and albedo on energy efficiency of buildings. The review focused on the energy usage reduction that can be achieved through the implementation of cool roofs. To achieve this goal, the literature review assessed 65 different papers related to the subject matter. The review considered a wide range of research studies, including academic papers, technical reports, and other relevant publications. The literature review investigated the impact of reflectance and albedo for TPO, EPDM, PVC, built-up roofs, asphalt shingles, metal roofs, concrete roofs, and clay tiles, further categorized roof systems into low slope and steep slope roofs.

3.1 Data Sample

The studies investigated for energy efficiency of various roof systems provides a comprehensive understanding of the geographical footprint as it is a critical factor that influences the efficiency of the system. The studies were analyzed in different regions of the world, including the United States of America, Asia, Europe, Australia, Africa, and South America. The sample size and the geographical distribution of studies is shown in Table 3 and Figure 1.

These studies were mainly focused on evaluating the energy-saving potential of cool roofs against a standard roof in different climatic zones and building types prevalent in the region. The standard roof system is the one without any modifications, such as coating, membrane color, insulation thickness, etc. The studies investigated and highlighted the various approaches and perspectives adopted to improve building's energy efficiency in different regions of the world.

Table 3: Sample size, location and climate of data points

Type of Roof	Sample size	Location	Sample size	Climate
Low Slope Roof	221	USA	47	Temperate, Sub-tropical climate
		Asia	77	Temperate, Sub-tropical, Sub-equatorial climate
		Europe	63	Temperate, Sub-tropical climate
		Others	34	Tropical, Sub-tropical, Equatorial, Sub-equatorial climate
Steep Slope Roof	137	USA	62	Temperate, Sub-tropical climate
		Asia	15	Temperate, Sub-tropical, Sub-equatorial climate
		Europe	25	Temperate, Sub-tropical climate
		Others	35	Tropical, Sub-tropical, Equatorial, Sub-equatorial climate

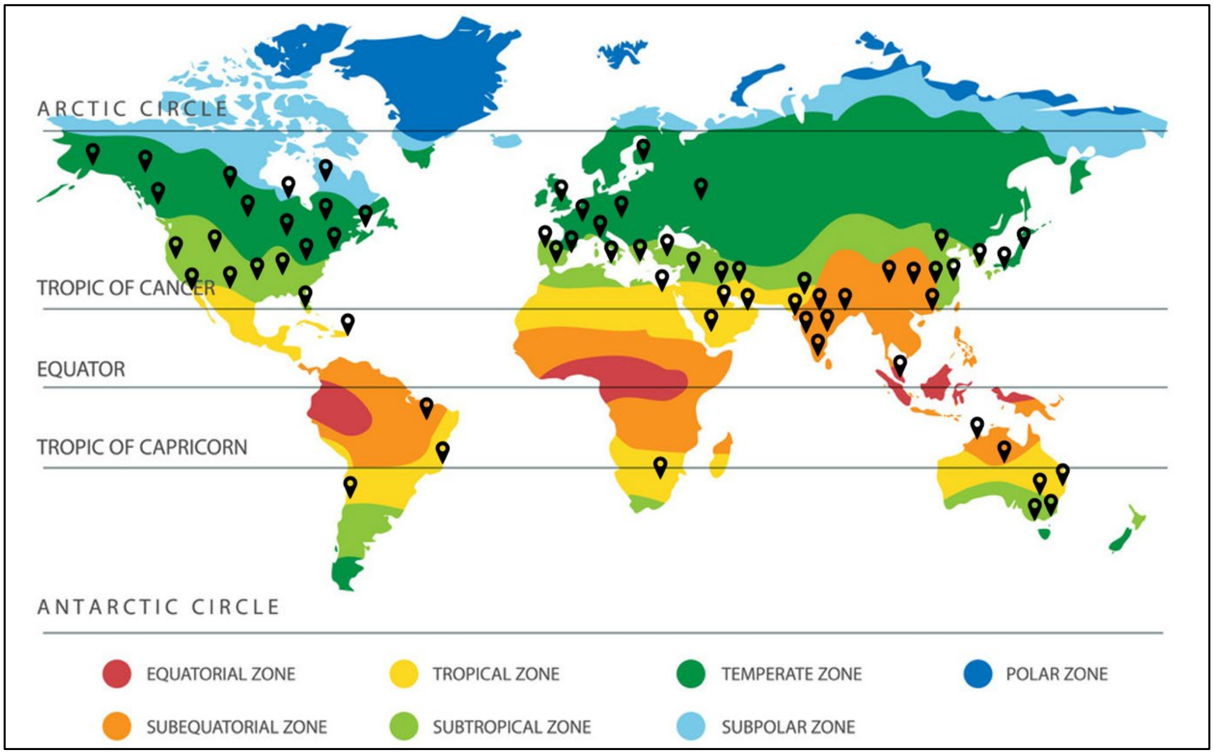

Fig. 1 – Geographical distribution of studies

3.2 Synthesis and Analysis of data

The graphs below show the effect of reflectance and albedo on energy efficiency of a building. Energy efficiency is defined as the percentage change in energy usage of a standard roof and a modified roof. The solar reflectance of a roof system is a product of the properties of the roof material and albedo is the lightness of a roof. Each of study shown in Figures 1, 2, and 3 are listed in the reference section.

Figure 2 shows the effect of reflectance on energy efficiency for low slope and steep slope roofs of all colors. For every change in reflectance by 10 units, there is an increase in energy efficiency by 4.5% for low slope roofs and 1.5% for steep slope roofs.

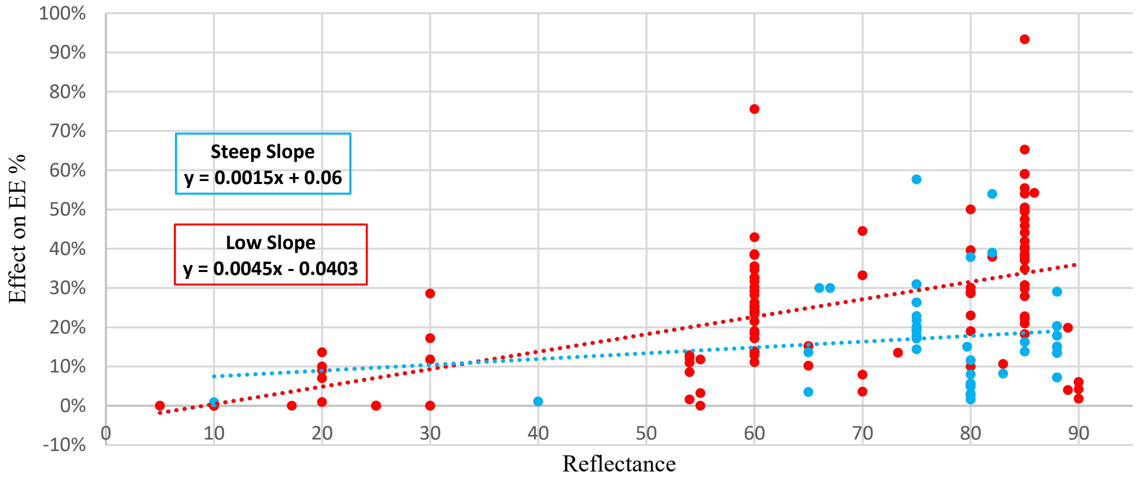

Fig. 2: Effect of Reflectance on Energy Efficiency

Low slope roofs have better performance with higher solar reflectance as it is a product of the material of the roof. Figure 3 shows the effect of albedo on energy efficiency for low slope and steep slope roofs of all colors. For every change in albedo by 0.1 units, there is an increase in energy efficiency by 2.2% for low slope roofs and 5.5% for steep slope roofs. Steep slope roofs have better performance with higher albedo as it is a product of the lightness of a roof membrane.

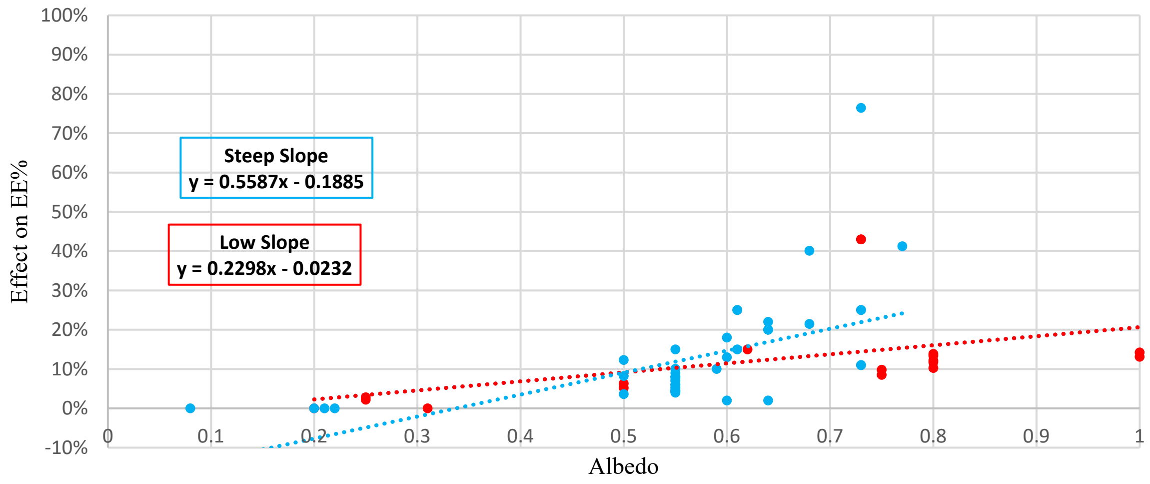

Fig. 3: Effect of Albedo on Energy Efficiency

Cool materials like liquid applied coatings or single ply membranes that have high reflectance result in surface temperature reductions ranging from 5 to 13 °C when compared to their equivalent conventional colors. (Levinson et al., 2007, Loh et al., 2010) A literature review study found that cooling energy savings range from 2% to 44% in residential and commercial buildings, with an average of around 20%. According to the literature, cool roofs can save between 3% and 35% on cooling energy, depending on ceiling insulation levels, duct placement, and attic structure. These findings, however, are only applicable to conventional US structures. (Haberl et al., 2004)

The existing research on the effect of installing a cool roof has been limited to isolated individual studies conducted in various parts of the world. Multiple studies have focused on data from certain months, which prevents the assessment of the roof's annual performance. There needs to be future studies that better document the impact of multiple variables changing simultaneously or identify them as limitations.

Moreover, the thermal insulation thickness plays a key role in reducing heat gains in hotter climates and minimizing heat energy loss in colder climates that also needs to be considered. In addition, the impact of insulation on energy efficiency needs to be modeled as against the impact of lightness of the roof. Additionally, the energy efficiency of a cool roof is often evaluated based on the cost savings achieved in different locations without normalizing the cost of electricity. It is essential to compare the cost savings as electricity cost can vary greatly from one location to another. Thus, in order to accurately evaluate the energy efficiency of a cool roof, it is important to consider multiple factors such as insulation thickness, cost of electricity, and the effect of multiple variables changing simultaneously and yet focus on comparing roofs in similar climate zones.

This systematic literature review aims to fill the gap in the current body of knowledge on the effectiveness of cool roofs in different climate zones. Due to the growing popularity of cool roofs and their potential benefits, it is critical to design a comprehensive study considering the impact of reflectance, albedo, and insulation on annual energy consumption along with envelope characteristics.

The primary goal of this study is to provide a comprehensive analysis of the roofing industry, consolidating the findings of multiple earlier studies to provide a true comparison between a standard roof and a cool roof. This study took various factors into consideration that affect roof performance and their impact on energy efficiency and realized the roofing industry needs a comprehensive study on cool roofs, their benefits, and challenges to keep up with recent advancements in the field. The value of this work lies in its ability to bring together the existing knowledge and provide a consolidated understanding of the effectiveness of cool roofs in different climate zones.

4. Conclusions

The paper evaluated various studies and their findings on the effect of cool roof on energy efficiency of low slope and steep slope roofs. Evaluating the energy efficiency of a building requires consideration of various factors, including solar reflectance, albedo and baseline energy usage values. The studies were analyzed in different regions of the world and the results show that with an increase in reflectance and albedo, the effect on energy efficiency increases. The baseline value of energy usage is an essential factor in determining the percentage of savings and energy consumption reduction. A lower baseline value shows a higher percentage of savings, but less energy consumption reduction than a higher baseline value. For e.g., in temperate and cold climates with a lower baseline case of energy usage, there are more percentage savings but less energy consumption reduction. As a result, future studies that focus on the impact of the changing climate, especially in temperate and cold climates on energy efficiency with various roof modifications (color, product type, insulation, etc.) are needed. Similarly, a study on life-cycle analysis to calculate the energy savings in terms of dollar value over the life of a roof with an emphasis on the cost-benefit analysis identifying effective roofing materials and designs is needed.

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