Through the Lens of Time: A Longitudinal Review of Energy Efficiency

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THE UNITED NATIONS' *Sustainable Development Report 2022*[1] ranks the US 41st out of 163 nations based on the 2022 SDG Index score of 74.6 (SDG Index is an assessment of the country's overall performance on the 17 Sustainable Development Goals [SDGs], giving equal weight to each goal). The country that was ranked first had a score of 86.5, whereas the country that was ranked 163rd had a score of 39. This report emphasizes the significance of having a sustainable building enclosure as a goal and area for progress for sustainable cities and communities.[1] The building sector has a detrimental influence on the environment since it is the biggest user of raw resources and waste production.[2] For example, nearly 40% of the total energy used in the US is used by residential and commercial buildings with both low-slope and steep-slope roofs.[3]

The energy used during the operation and maintenance of buildings includes the energy required for lighting, heating, cooling, and ventilation systems, as well as the energy used by electronics, appliances, and other equipment. Strategies to decrease energy consumption include improvements to building insulation, effective heating and cooling systems, and efficient building enclosures. According to Costanzo et al.,[4] roofs comprise 20% to 25% of building surfaces in urban settings. Furthermore, roof systems are essential for a building's thermal performance because they can account for up to 50% of the structure's overall thermal load.[5] Modifications to the roof's surface, such as coating the roof surface to change the albedo value and the use of materials that alter the reflectance of the roof's surface, are some of the ways to improve the energy efficiency of building enclosures.[6]

Key factors in the energy efficiency of roofing systems are solar reflectance and albedo. Solar reflectance is the roofing system's ability to reflect solar energy into the atmosphere and is measured using the solar reflectance index (SRI) on a scale from 0 to 100. ASTM E1980-11 standards state that SRI = 100 for a standard white surface and SRI = 0 for a standard black surface.[7] In this study, the terms *solar reflectance* and *solar reflectance index* have been used interchangeably. Albedo is the percentage of incident radiation reflected off a surface (such as the surface of a roof).[8] The building's temperature will rise as the building absorbs solar radiation that the roofing system does not reflect. A surface with an albedo value of 0 absorbs 100% of solar radiation, whereas a surface with an albedo value of 1 absorbs 0% of solar radiation.

To assess how changes in the solar reflectance and albedo of roofing systems affect energy efficiency, we collected and analyzed data from relevant studies published from 1990 to 2019. The goals of this study were to (a) conduct a systematic literature review of studies documenting the impact of a roofing membrane's solar reflectance and albedo on a building's energy efficiency; (b) synthesize the data and findings from the various studies; and (c) suggest areas where further research is warranted.

METHODOLOGY

A systematic literature review entails conducting a thorough search to find pertinent material. Databases, journals, conference proceedings, and other sources can be used in this type of review. In this study, we initially identified literature published between 1990 and 2019 with the following keywords: roof, energy efficiency, temperature, albedo, reflectance, and insulation. To narrow these results, we

Table 1. Search results and database keywords

Database	No. of articles found	No. of papers included in review
Engineering Village	178	12
ProQuest	287	3
ACM [Association for Computing Machinery] Digital Library	1	0
Web of Science	234	7
Business Source Complete	20	2
Academic Search Complete	97	10
Springer Link	172	2
Institute of Electrical and Electronics Engineers	32	1
Wiley Online Library	71	2
Office of Scientific and Technical Information	121	5
Clemson Library	313	27
Other Sources	165	6
Total	1,691	77

Table 2. Selection of relevant articles

Step	Results
Step 1: Initial identification based on keywords	1,691 articles identified
Step 2: Refinement of selection based on inclusion criteria and study design	747 articles selected
Step 3: Review of articles and abstracts to identify articles relevant to the aims of the literature review	325 articles eligible
Step 4: Review of articles that include the effect of roofing systems on energy efficiency in the main body	77 articles included

then followed up with content and comparative analysis, in which we used various approaches to search dedicated words and word associations, such as narrative summary, content analysis, case, survey, and comparative analyses.[9]

Table 1 shows the results of a search that was run on 12 databases using the keywords and their Boolean logic combinations to identify potentially relevant publications across various databases.[9,10] This initial search retrieved 1,691 articles. Table 2 summarizes the process for selecting the relevant articles. The inclusion criteria were (a) only peer-reviewed publications; (b) articles with data on various types of roofing systems and the impact of system type on energy efficiency as measured by cooling/heating energy usage, dollar savings, and temperature reductions; (3) cases from

anywhere in the world; and (4) authenticity of the source.[11] Studies either compared the same type of roofing system for different locations or compared the same type of roofing system for varying albedo and reflectance values.

The factors that were extracted from the literature review included the sample size (number of roofs investigated), study locations and climates, the albedo of the roof membranes, the solar reflectance of the roof membranes, the types of roofing systems, relative energy savings from an original roof versus a modified roof, study limitations, and conclusions.

The sample size discussed in Table 3, representing the individual instances of roofs included in the studies was 538, of which 395 were low-slope roofs and 143 were steep-slope roofs. 52% of the sample

size evaluated existing roof membranes that were coated afterwards. In comparison, 19% measured the effect of change in the albedo value of the roof by applying a coating or modification to the membrane. 12% of the studies documented the effect of change in insulation, while 9% recorded baseline cases comparing different types of roofs. The distribution of studies across the climatic zones is listed in Table 3.

Albedo and solar reflectance values of the original roof and of the modified roof were documented. Energy efficiency is defined as the percentage change in energy usage between the original roof and the modified roof. The charts were then plotted using the above-recorded data points to interpret the relationship between solar reflectance or albedo of the modified

Table 3. Locations, climates, and sample sizes

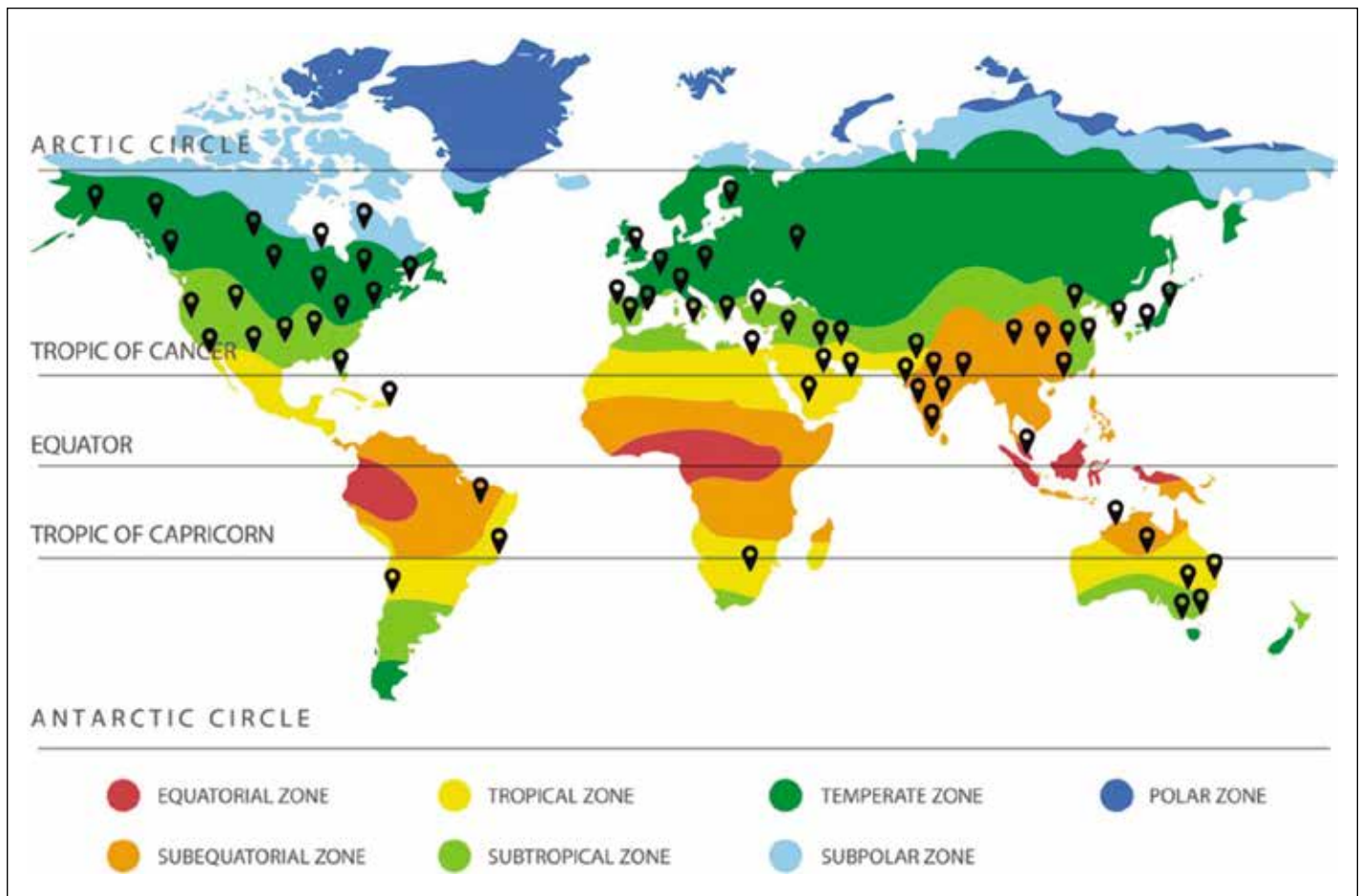| Location	Climates	Sample size for low-slope roofs	Sample size for steep-slope roofs	Total sample size
US	Temperate, subtropical	202	65	267
Asia	Temperate, subtropical, subequatorial	79	15	94
Europe	Temperate, subtropical	64	27	91
Other	Tropical, subtropical, equatorial, subequatorial	50	36	86
Total		395	143	538

Figure 1. *Geographical distribution of studies in the literature review.*

roof with the energy efficiency calculated as a percentage difference.

RESULTS AND DISCUSSION
A systematic literature review was conducted to examine how reflectance and albedo affect a building's ability to use energy efficiently. To accomplish this goal, 77 publications on the topic, including scholarly articles, technical reports, two literature reviews, and other pertinent publications were evaluated.

Data Sample
This study included published studies from the US, Asia, Europe, Australia, Africa, and South America. Table 3 and **Fig. 1** show the sample sizes and the geographical distribution of studies, respectively. The studies were evaluated for the energy savings between the original roof system installed (those without any modifications, such as coating, membrane color, or changing *R*-value) and modified roofing systems.

Data Synthesis and Analysis
Figures 2 and **3** plot the effects of solar reflectance and albedo on the energy efficiency of buildings, where energy efficiency is defined as the percentage change in energy usage between buildings with the original roofing system and a modified roof roofing system. Energy usage was measured in GJ (gigajoules) per year and kWh (kilowatt-hour) per time or area (for example, kWh per m^2 or kWh per day). Out of 77 studies, only 4 studies investigated
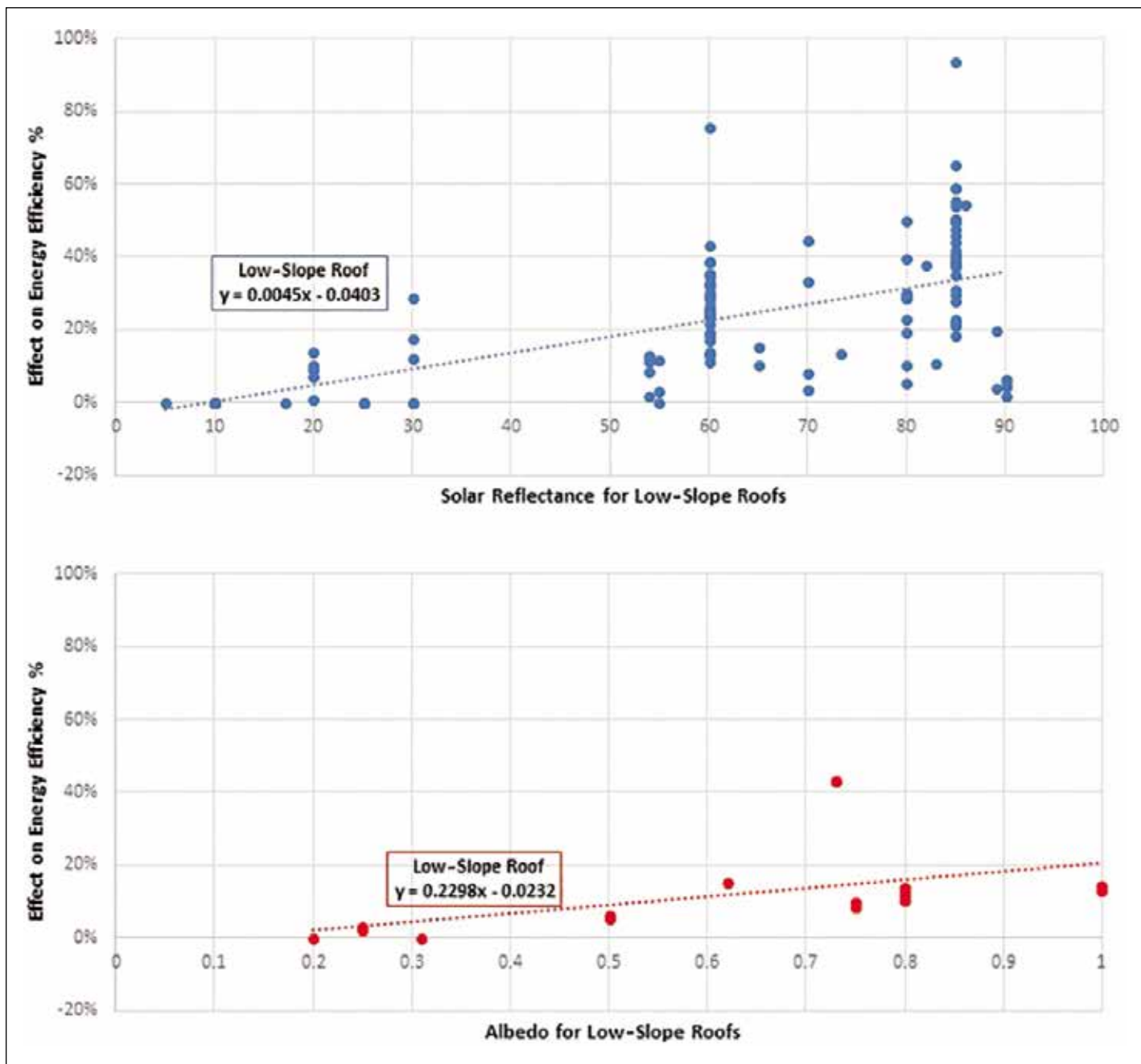
Figure 2. *Effects of solar reflectance and albedo for low-slope roofs on energy efficiency.*

utility bills, while 58 studies were modeled for energy usage.

Figure 2 includes data on low-slope roofing systems of all colors, and Fig. 3 includes data on steep-slope roofing systems of all colors. For every 10-unit change in solar reflectance, energy efficiency increases by 4.5% for low-slope roofs and 1.5% for steep-slope roofs. For every 0.1-unit change in albedo, energy efficiency increases by 2.2% for low-slope roofs and 5.5% for steep-slope roofs.

Based on the study, changing the albedo value of the roof and altering the reflectance value of the roof has a different effect on energy efficiency on a low-slope roof versus a steep-slope roof. Higher energy efficiency is observed in low-slope roofs with a change in reflectance of the roof. In contrast, higher energy efficiency is observed in steep-slope roofs with a change in the albedo value of the roof.[12]

Table 4 identifies the parameters of the roofing system that the 75 studies (excluding the 2 literature-review studies) considered to be integral influences on energy efficiency. The table shows the number of studies that included or excluded each of the parameters. Notably, while all studies considered location to be a critical factor, only 36% of the studies considered

insulation as a key parameter. Further, 32% of the studies included albedo as an important factor, whereas 70% of the studies considered reflectance as an integral parameter.

CONCLUSION

The main objective of this study was to conduct a systematic literature review to offer a thorough examination of the roofing sector by synthesizing the results of past investigations. The literature review demonstrated that significant energy efficiency research has been conducted for different types of roofing systems. The findings of this systematic literature review indicate
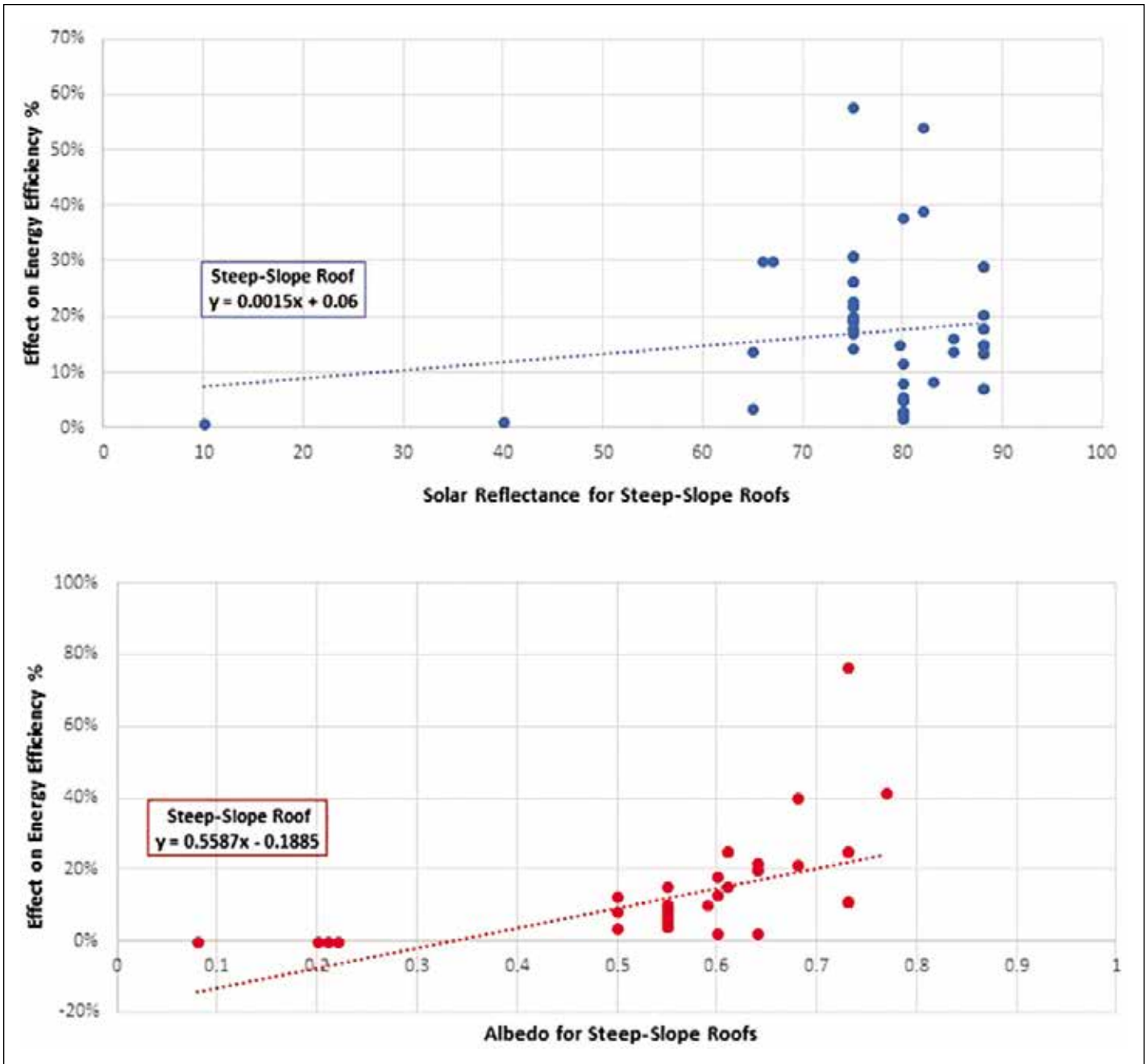
Figure 3. *Effects of solar reflectance and albedo for steep-slope roofs on energy efficiency.*

that as solar reflectance and albedo increase, energy efficiency also increases. The systematic literature review also identified other parameters that were included in the studies that impact a building's energy efficiency.

Time of data capture was one of the parameters identified. Some of the observations from the literature review illustrate the need to evaluate the roofing system's effects on energy performance over the entire year, rather than on data from specific months in the year. Additionally, the *R*-value of the insulation needs to be considered, which is essential because it can minimize heat energy loss in colder climates and reduce heat gains in hotter ones. A higher balance of real-world studies is also necessary vis-à-vis simulation/energy-model-based studies. For meaningful comparison in dollar value, the cost savings need to be normalized for different regions because electricity prices can differ substantially from one place to another. Roofing systems also need to be compared in climate zones with similar climatic conditions to better assess the energy efficiency. In summary, along with solar reflectance and albedo value, it is recommended to consider other parameters such as the months in the year when the study was conducted, insulation *R*-value, energy costs, and different climate zones to better assess the effects of roofing systems on energy efficiency. Life-cycle analyses would also be interesting to discover appropriate roofing materials and designs and evaluate energy savings throughout the life cycles of roofing systems.

This study acknowledges the breadth of research that has already been conducted in the roofing industry on the topic of energy efficiency. This study suggests a path forward for the roofing industry to direct and design future studies on energy efficiency that benefit the industry, buildings, and the environment. ⬥IIBEC

Table 4. List of parameters used to study the effect on energy efficiency

Parameter	Parameters included, no. of studies	Parameter not included, no. of studies	N/A*
Sample size (average) = 7.17			
Properties of roof			
Color of roof	48	27	
Area of roof	54	21	
Insulation	27	48	
Solar reflectance	52	23	
Albedo	24	51	
Study design			
Real-world study	17	58	
Simulation-based study	58	17	
Hot weather	53	0	22
Cold weather	14	39	22
Location	75	0	
Duration of data capture	53	0	22

* N/A represents the simulation-based studies in which data was simulated for effect on energy efficiency for the whole year

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