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Systematic Literature Review of Roof Systems on Energy Efficiency of a Building to Support an Ideal Study Framework

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SYSTEMATIC LITERATURE REVIEW OF ROOF SYSTEMS ON ENERGY EFFICIENCY OF A BUILDING TO SUPPORT AN IDEAL STUDY FRAMEWORK

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ABSTRACT

A sustainable building envelope is a crucial element to build energy efficient structures that contribute towards sustainable communities. The demand for sustainable building envelopes has grown in response to a growing emphasis on sustainable living. The roofing system is an important component of a sustainable building envelope because it influences the building's energy consumption and indoor comfort levels. The current study focuses on roofing systems and associated solar reflectance and albedo values to document the impact on energy efficiency via cooling/heating energy usage, dollar savings and temperature (ambient and surface) reductions due to the roofing systems. Additionally, the study focuses on organizing the data and findings based on study design parameters to capture the changing efficiency over solar reflectance and albedo values. The PSALSAR framework was used to conduct a systematic literature review. The framework compares the documented data from various literature sources with increasing solar reflectance and albedo values and its impact on energy efficiency. The systematic literature review considered data from 77 papers to analyze parameters like solar reflectance and albedo for different types of roofs, identifying key limitations and gaps using a survey that paves 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 the implementation of cool roofs.

DEDICATION

To my parents and my brother, who have been my unwavering pillars of support throughout my journey. For their love, encouragement, sacrifices, and faith in me. To my grandmother with me in spirit, cheering me on.

ACKNOWLEDGMENTS

I am incredibly grateful to my thesis advisors, Dr. Dhaval Gajjar, Dr. Vivek Sharma, and Dr. Jason Lucas, for their support, expertise, and encouragement throughout my research journey. Their guidance and knowledge have been instrumental in developing and finishing this thesis.

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I want to express my deepest gratitude to my family for their love and support. Their belief in my abilities has been a driving force in my academic journey. I am grateful for their numerous sacrifices to get me where I am today.

I sincerely appreciate and am grateful to every person who has helped me in my academic endeavors. I am honored to have had this opportunity to learn and grow, and I will always carry the lessons learned under this mentorship with me.

TABLE OF CONTENTS

Table of Contents (Continued) Page

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE

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). Currently, 55% of the world's population lives in urban areas, and is expected to increase to 68% by 2050 (Luangcharoenrat et al., 2019). In 2020, buildings' global construction and operation represented a significant portion of the world's energy consumption, accounting for approximately 36 percent of global energy consumption (149 exajoules (EJ). Of these, 127 EJ of energy was consumed during the operation and maintenance of buildings (Global Status Report for Building and Construction 2021).

Construction is one of the industries with the most significant potential for enhancing global energy efficiency and sustainability through low-cost techniques (Ascione et al., 2016). The construction industry uses 35% of the produced energy and releases 40% of CO_2 into the earth's atmosphere. The construction industry is the largest consumer of raw materials and produces waste material, which negatively impacts the environment (UN Environment, 2017). 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 and the energy consumed by electronic devices, appliances, and other equipment used in the building. This energy consumption is influenced by various factors, such as building design, insulation, and the efficiency of the building's systems and equipment. Reduction in energy consumption of buildings can contribute to climate change and greenhouse gas emissions. Various strategies, such as building insulation, efficient heating and cooling systems, and efficient building envelope, such as the use of efficient roof systems in building design, can help reduce energy consumption. The building's envelope impacts energy use and contributes to thermal comfort. Building envelopes minimize energy consumption by lowering glare, eliminating water penetration, providing natural ventilation, reducing external reflection, offering a view, and functioning as a thermal barrier while insulating the interior from direct solar radiation penetration (Mirrahimi et al., 2016). Roofs account for approximately 20%-25% of building surfaces in urban areas (Costanzo et al., 2014). Additionally, roof systems are critical to the thermal performance of a building as it contributes up to 50% of the total thermal load of the building (Nahar et al., 2003). Some solutions include modifications on the roof's surface, such as changing the color or utilizing highly reflective materials. (Boixo et al., 2012) Among all building envelope components, the roof experiences the greatest temperature variations on clear days, rainy days, night hours, and seasons (Piselli et al., 2017; Hernández-Pérez et al., 2014).

Multiple studies over the last few decades have documented the evolution of different roofing systems and their impact on the energy efficiency of a building. The current research looks back in time, collates the findings, and analyzes the impact of changing albedo and solar reflectance on energy efficiency. Solar Reflectance measures the roof's capacity to reflect a fraction of solar energy back into the atmosphere (scale 0-100) (Muscio, 2018). Under the same solar energy exposure, surfaces with a greater SR will be cooler than surfaces with a lower SR, especially on a sunny day. Using materials with greater SR values can improve occupant comfort while reducing air conditioning use. Albedo is the proportion of incident radiation reflected from the roof's surface (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. A regular white material reflects the majority of solar energy in the visible range (0.4–0.7 m); this material will keep the roof cooler than an unpainted one (Hernández-Pérez et al., 2014).

Study Objectives

Research Objective 1.1: Conduct a systematic literature review to document the effect of solar reflectance and albedo of the roofing membrane on the energy efficiency of a building.

Research Objective 1.2: To organize the data and findings based on study design parameters to capture the changing efficiency over solar reflectance and albedo scores.

Research Objective 2: Formulate a framework for an ideal/comprehensive study using study design parameters to compare energy efficiency of a standard and cool roof.

Building Envelope and Thermal Comfort

A building is divided into two main components: opaque and transparent. In addition to providing thermal comfort, it is designed to protect the building from the outdoor environment. Utilizing a building envelope that is poorly designed will result not only in a decrease in thermal comfort but also an increase in energy consumption. Simply put, how a building's exterior is designed impacts its energy use. The roof experiences the most significant temperature variations even though all components of the building envelope are in contact with the outside environment. The impact of solar radiation on clear days, heat loss in the infrared during the night, and rain all have a greater impact on the roof than any other building component.

Roofing and the its effect on thermal performance of a building

As the roof plays a crucial role in the thermal performance of a building, there is a need to implement passive measures to reduce the influence of roofs on the heat gain of the building. (Hernández-Pérez et al., 2014) There are passive architectural measures that reduce the heat gain from the roof by altering the geometry of the roof. For e.g., an opening on the crown of a dome helps in the escape of heated air in the building and increases ventilation. The non-architectural passive measures are independent of roof geometry and are installed in either the interior or exterior of the roof (Ashtari et al., 2021).

Cool materials like liquid-applied coatings or single-ply membranes with high reflectance result in surface temperature reductions ranging from 5 to 13 °C compared to their equivalent conventional colors (Levinson et al., 2007; Loh et al., 2010). A literature review 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 individual studies that are isolated in specific parts of the world. These studies have conclusions based on limited data collected for certain months of the year, which needs to reflect the annual energy performance of the roof accurately. Additional steps in the methodology must be considered when calculating annual energy performance. Multiple variables like location and climate change simultaneously and have yet to be considered while drawing conclusions in existing studies. This leads to confounding results on the impact of a cool roof on energy efficiency.

Moreover, thermal insulation is a factor that significantly affects the energy efficiency of a building by reducing heat gains in hotter climates and minimizing heat energy loss in colder climates. This is a crucial factor when evaluating the performance of a cool roof. Additionally, the energy efficiency of a cool roof is often assessed based on the cost savings achieved in different locations without normalizing the cost of electricity. This approach does not allow for meaningful comparisons as electricity costs vary from location to location. Thus, to accurately evaluate the energy efficiency of a cool roof, multiple factors such as insulation thickness, cost of electricity, and the effect of multiple variables changing simultaneously must be considered.

This systematic literature review aims to fill a knowledge gap on the effectiveness of cool roofs with varying factors in different climate zones. Despite the potential benefits of cool roofs, a comprehensive study has yet to be conducted that examines the impact of reflectance, albedo, and insulation on annual energy consumption and envelope characteristics.

The main objective of the research is to provide a comprehensive analysis of the roofing industry by consolidating previous studies' findings and giving an accurate comparison between a standard roof and a cool roof. This research will consider the various factors that influence the performance of a roof and their impact on energy efficiency.

To keep up with recent advancements in the field of sustainable building envelopes, the roofing industry requires a comprehensive review of cool roofs, their benefits, and their challenges. This research will lay the groundwork for future research and implementation by the construction industry by providing practical knowledge of cool roofs. The value of this work lies in its ability to synthesize existing knowledge and provide a comprehensive understanding of the effectiveness of cool roofs across a range of climates.

CHAPTER TWO

METHODOLOGY

Framework for RO – 1

This study examines the effect of changing albedo and reflectance scores on energy efficiency for various roofing systems. The PSALSAR framework (Andriuškevičius et al., 2022) was used to identify factors affecting roof performance and conduct a systematic literature review in six phases as shown in Fig 1.

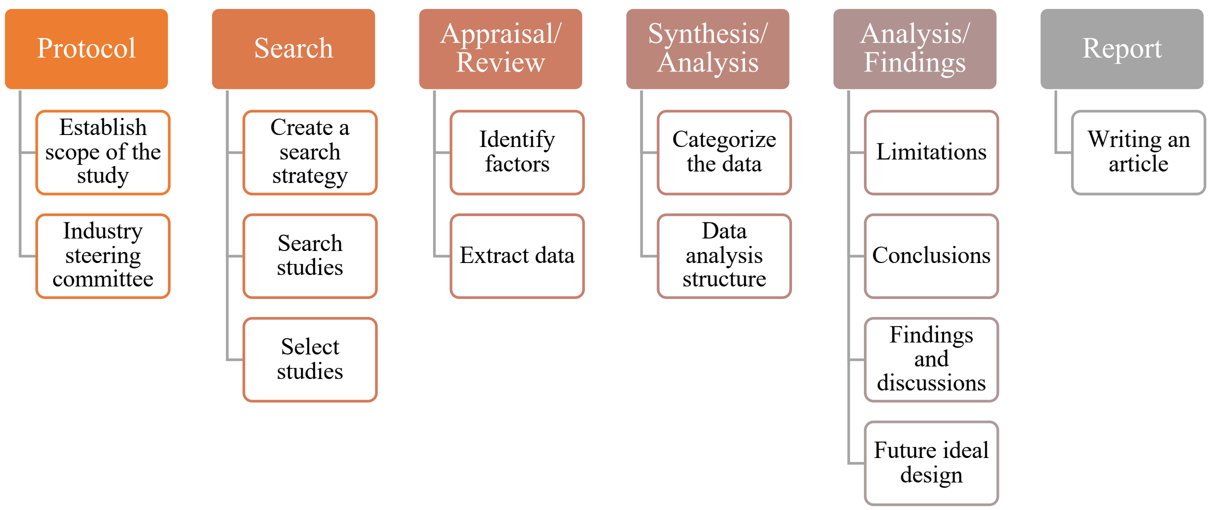

Figure 1: Framework for RQ 1

PSALSAR is an acronym for Protocol - Search - Appraisal - Synthesis/Analysis - Analysis/Findings - Report. It is the framework to conduct an extensive literature review and search to evaluate the parameters for the impact of roof system modification on the energy efficiency of a building.

- Phase 1 – Protocol: This phase involves defining the literature review's research question, objectives, and methodology.

- Phase 2 – Search: In this phase, a comprehensive search is conducted to identify relevant literature. This included databases, journals, conference proceedings, and other sources.

- Phase 3 – Appraisal: The identified literature is evaluated for its relevance and quality in this phase. This includes assessing the methodology used, the results obtained, and the conclusions are drawn.

- Phase 4- Synthesis/Analysis: This phase involves synthesizing and analyzing the data collected from the literature. The data is then summarized and organized into themes to facilitate the analysis.

- Phase 5 – Analysis/Findings: In this phase, the data is analyzed to document the effect of reflectance and albedo of roofing membrane on the energy efficiency of a building. This phase also examines the relationships between the study design parameters and changing energy efficiency.

- Phase 6 – Report: The final phase involves presenting the results of the literature review in a clear and concise manner. This includes a summary of the findings, recommendations for future research, and study limitations.

Table 1 shows the framework for a systematic literature review using the PSALSAR approach and the methods used to reach the outcomes of each phase.

Table 1: PSALSAR framework for systematic literature review

	Steps	Outcomes	Method
Framework for SLR	Protocol	Establish scope of the study	
	Search	Create a search strategy Search studies Select studies	Identify keywords Search databases Identify inclusion/exclusion criteria
	Appraisal/ Review	Identify factors Extract data	Background study
	Synthesis/ Analysis	Categorize the data Data analysis structure	Based on factors identified Framework to quantify EE
	Analysis/ Findings	Findings and discussions Limitations Conclusion	Result and trends Identify the gap Conclusion and recommendation
	Report	Summary and results	

Protocol

The Systematic Literature Review (SLR) presented in this article follows a structured approach to assess the impact of roof performance on energy efficiency. The purpose of the SLR was to investigate the findings of past studies that have attempted to identify and quantify the factors that impact energy efficiency in the roofing industry. The first stage of the SLR was to define the scope and objectives of the study through an industry steering committee. The steering committee provided guidance and feedback for Phase 2 and Phase 3 and validation through Phase 5 of the PSALSAR approach.

Search

With various approaches to searching dedicated words and word associations in a literature review, such as narrative summary; thematic analysis; grounded theory; content analysis; case, survey, comparative analysis; and Bayesian meta-analysis, this study identified literature with the defined keywords in the beginning and followed up with "snowballing" the meaningful literature (Sharma et. al., 2022). Various combinations of keywords including, but are not limited to, 'cool roof', 'energy efficiency', 'albedo', 'reflectance', and 'insulation'. Table 2 shows the results of a search run on eleven (11) databases using a combination of the keywords mentioned above.

Table 2: Search results by database

<table>
<tr><th>S. No.</th><th>Database</th><th># of articles</th><th># of inclusion criteria</th><th>Key words</th></tr>
<tr><td>1</td><td>Engineering Village</td><td>178</td><td>14</td><td rowspan="12">"cool roof" AND "energy efficiency"

"cool roof" AND "temperature"

"cool roof" AND "albedo"

"cool roof" AND "reflectance"

"cool roof" AND "insulation"</td></tr>
<tr><td>2</td><td>ProQuest</td><td>287</td><td>5</td></tr>
<tr><td>3</td><td>ACM Digital Library</td><td>1</td><td>0</td></tr>
<tr><td>4</td><td>Web of Science</td><td>234</td><td>7</td></tr>
<tr><td>5</td><td>Business Source Complete</td><td>20</td><td>2</td></tr>
<tr><td>6</td><td>Academic Search Complete</td><td>97</td><td>10</td></tr>
<tr><td>7</td><td>Berkeley Lab Heat Island Group</td><td>165</td><td>6</td></tr>
<tr><td>8</td><td>Springer Link</td><td>172</td><td>6</td></tr>
<tr><td>9</td><td>IEEE</td><td>32</td><td>1</td></tr>
<tr><td>10</td><td>Wiley Online Library</td><td>71</td><td>2</td></tr>
<tr><td>11</td><td>OSTI</td><td>121</td><td>7</td></tr>
<tr><td>12</td><td>Clemson Library</td><td>313</td><td>17</td></tr>
<tr><td></td><td>Total</td><td>1,691</td><td>77</td><td></td></tr>
</table>

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). Following the initial search, non-peer-reviewed research articles and proceedings were excluded. 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 and temperature reductions; (3) research studies from all over the world; and (4) authenticity of the source.

The various search results from all the databases were further categorized in Table 3 based on the Boolean logic combinations of keywords.

Table 3: Article selection

IDENTIFICATION	**Initial identification based on keywords**
	1691 articles identified
SELECTION	**Narrowing down initial identification based on inclusion criteria, peer reviewed articles and study design**
	747 articles selected
ELIGIBILITY	**Review of articles and abstract to identify articles relevant to the aims of this paper**
	325 articles eligible
INCLUSION	**Review of articles that quantify the effect of cool roof on energy efficiency**
	77 articles included

Appraisal / Review

The steering committee comprised subject matter experts (SMEs) who were involved in identifying and validating factors that affect the energy efficiency of a building. The following factors were identified through an extensive literature review.

- Type and sample size of the roofs investigated, study location, climate, temperature range, the color of the roof membrane (albedo and reflectance scores), the duration of data capture, type of study (case study or simulation-based), study limitations, and conclusions.

Synthesis/Analysis

At the data extraction stage, the relevant information from the selected articles was extracted to determine the effect of various roofing systems on energy efficiency. This process involved collecting data from each article that can be used for synthesizing and analyzing the data. The raw data was organized based on the study design parameters and the factors that were identified in the appraisal and review phase. There are twelve (12) study design parameters – Sample Size, Area of Roof, Location, Color, Insulation, Reflectance, Albedo, Hot Weather, Cold Weather, Duration, Simulation, and Real-World. These parameters are defined in Appendix – A. Studies are organized based on the inclusion of these parameters in their analysis for the effect of a cool roof on energy efficiency. In addition, the limitations and findings of the study were synthesized and analyzed with respect to the validity and reliability of the findings.

Analysis/Findings

The data analysis stage involved evaluating the synthesized data to derive pertinent information that addresses the research questions. The goal of this stage was to identify patterns, trends, and relationships in the data, as well as to draw meaningful conclusions from the data. The data analysis process involved systematically reviewing the collected data, categorizing it in accordance with the established criteria, and identifying patterns and themes. The data collected from the studies was categorized into the above-mentioned twelve (12) parameters to identify themes and patterns in the type and methodology of the studies. In the end, the steering committee validated the results.

Report

The final phase involves presenting the results of the literature review in a clear and concise manner which includes a summary of the findings, recommendations for future research, and limitations of the study.

Framework for RO – 2

Identifying and classifying data from relevant studies is essential to develop the framework for an ideal study. The primary goal is to identify the inclusion of different parameters in the studies that affect the energy efficiency of a building. The next step was to conduct a survey within the industry to understand the perception of roofing professionals regarding these parameters that impact roof performance and the energy efficiency of a building. The survey results will be used to design a framework for an ideal study focusing on the most important parameters impacting roof performance and making a building energy efficient.

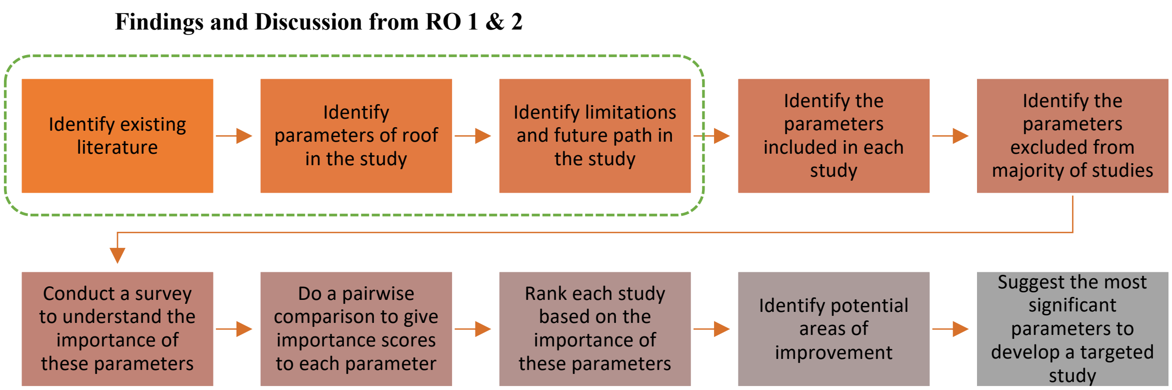

Figure 2: Framework for RQ 2

There are twelve (12) parameters identified from RO 1 & 2. Sample Size, Area of the roof, Location, Color, Insulation, Reflectance, Albedo, Hot weather, Cold weather, Duration, Simulation and Real World. The pairwise comparison survey importance scores ranked the parameters according to their relative significance. The study's parameters that should be further investigated can be decided using this ranking. For instance, if the survey results indicate that insulation is the most critical parameter, the study can look at the efficacy of various insulation types and how they affect energy efficiency. Based on ten (10) survey responses, these parameters were compared using the following table. The survey is in Appendix B.

Table 4: Pairwise comparison matrix for parameters

	Sample Size	Area of Roof	Location	Color	Insulation	Reflectance	Albedo	Hot Weather	Cold Weather	Duration	Simulation	Real-World
Sample Size												
Area of Roof												
Location												
Color												
Insulation												
Reflectance												
Albedo												
Hot Weather												
Cold Weather												
Simulation												
Real-World												

The Analytical Hierarchy Process (AHP) was used to weigh the rankings of each parameter. To conduct the survey, professionals from the industry were asked to rate each parameter compared to the others. In order to build a matrix that represents this pairwise comparison, the responses were recorded. After normalizing the pairwise comparison, the geometric means of each row were computed to determine the weights for each parameter. Thus, a set of weights were produced, each of which denotes the pertinent significance of a particular parameter. By multiplying the weights by the scores for each parameter, the overall priorities for each parameter were determined. A final weighted ranking of the different parameters was calculated based on their relative importance.

CHAPTER THREE

RESULTS AND DISCUSSION

The purpose of the systematic literature review was to analyze the impact of reflectance and albedo on the energy efficiency of buildings. The study focused on energy usage reduction, dollar savings, and temperature reduction that can be achieved by implementing cool roofs. To achieve this goal, the literature review assessed 77 papers covering a broad spectrum of research studies, including academic papers, technical reports, and other relevant publications. The papers were selected based on the relevance to the subject and the methodologies used to investigate the relationship between reflectance, albedo, and energy efficiency. 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. Additionally, the studies were further categorized into roof systems - low slope and steep slope roofs; and research methodology - simulation and real-world based studies.

Data Sample

The studies investigated for energy efficiency of various roof systems provide 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. These studies were mainly focused on evaluating the energy-saving potential of cool roofs against standard roofs 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 effect of these modifications on energy efficiency was calculated by taking the energy usage with a standard roof as the base case scenario and any decrease in usage as the positive effect on energy efficiency. The studies investigated and highlighted the various approaches and perspectives adopted to improve building energy efficiency in different regions of the world.

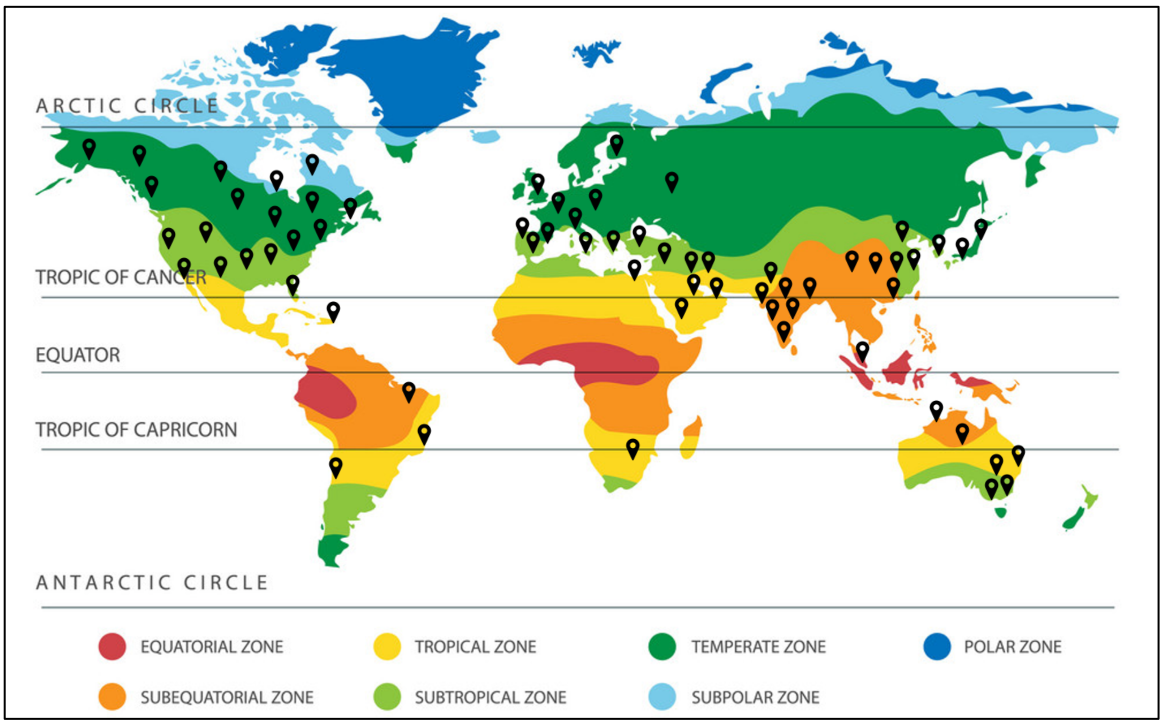

Figure 3: Geographical distribution of studies

Figure 3 presents the geographical distribution of various data points used in the studies analyzing the energy efficiency of roofs. The data points were collected from around the world and categorized based on their geographical location.

In terms of geographical distribution, out of the seventy-seven (77) studies, twenty-eight (28) studies were conducted in the United States of America, which was the location with the highest number of studies. Twenty-two (22) studies were conducted in Europe, while sixteen (16) studies were conducted in Asia. The remaining nineteen (19) studies were conducted in other locations, namely Australia, Africa, and South America.

Fifty-six (56) studies analyzed data points located between the Arctic Circle and Tropic of Cancer, covering a vast region in the northern hemisphere. Nine (9) studies analyzed data points located between Tropic of Cancer and Equator, covering primarily tropical and subtropical regions. Five (5) studies analyzed data points located between Equator and Tropic of Capricorn, covering regions in South America, Africa, and Australia. Lastly, six (6) studies analyzed data points between Tropic of Capricorn and Antarctic, including regions in South America, Africa, and Australia.

Table 5: Distribution of data points

Type of Roof	Location	Sample size
Low Slope Roof	USA	202
	Asia	79
	Europe	64
	Others	50
Total		**395**
Steep Slope Roof	USA	65
	Asia	15
	Europe	27
	Others	36
Total		**143**
Simulation	USA	222
	Asia	92
	Europe	75
	Others	78
Total		**467**
Real-World	USA	45

	Asia	2
	Europe	16
	Others	8
Total		**71**

Table 5 depicts the distribution of studies investigating the energy efficiency of roofs in different regions of the world. Out of the seventy-seven (77) studies analyzed, fifty-eight (58) were simulation-based studies, seventeen (17) were real-world studies, and two (2) were literature reviews. Out of the total sample size, three-hundred ninety-five (395) were low-slope roofs, and one-hundred forty-three (143) were steep-slope roofs. With the categorization of the same data points into study methodology, there were four-hundred sixty-seven (467) data points for simulation-based studies and seventy-one (71) data points for real-world studies. The majority of the studies in all four categories were done in the USA, followed by Asia, Europe, and others.

Figures 4 and 5 show the data capture duration for low slope, steep slope, real-world and simulation-based studies. The median value of data capture for real-world studies is between 90-100 days, and for simulation-based studies is between 250-300 days. Real-world studies are experiments carried out for a specific duration, considering all seasonal changes and temperature variations. Whereas for simulation-based studies, data is captured for a few days to calibrate the simulation model and further predict the energy efficiency for the year. Here a duration of 365 days for simulation-based studies means that data captured for specific days during different climates was extrapolated to find out energy efficiency for the whole year.

Figure 4: Duration of steep slope and low slope studies

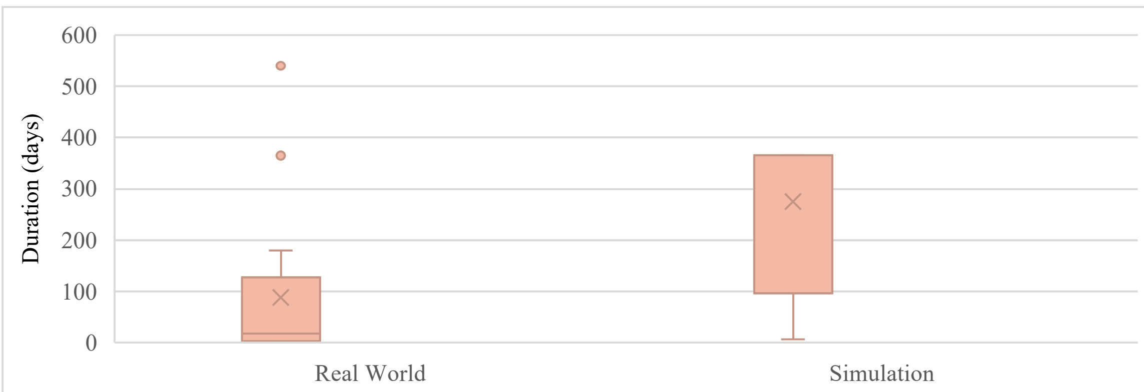

Figure 5: Duration of real-world and simulation-based studies

Low Slope vs Steep Slope

The data below shows the effect of reflectance and albedo on the energy efficiency of a building for low slope roof and steep-slope roof-based studies. Energy efficiency is defined as the percentage change in energy usage of a standard roof and a roof system modification.

Table 6 presents the different types of roof system modifications that were made on low-slope and steep-slope roofs. Out of a total of four-hundred sixty-nine (469) roof system modifications, three-hundred fifty-two (352) were modifications made on low-slope roofs, and one-hundred seventeen (117) were modifications made on steep-slope roofs. Modifications for low-slope roofs were further divided into two-hundred sixty-six (266) coating-based, fifty-four (54) insulation changes, and thirty-two (32) membrane-based modifications.

Table 6: Roof system modifications for low slope and steep slope roofs

Type of Study	Roof System Modification	Sample size
Low Slope Roof	Coating - based	266
	Insulation change	54
	Membrane - based	32
Steep Slope Roof	Coating - based	117
Total Roof System Modifications		**469**

Figure 6 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. Low slope roofs have better performance with higher solar reflectance as it is a product of the material of the roof.

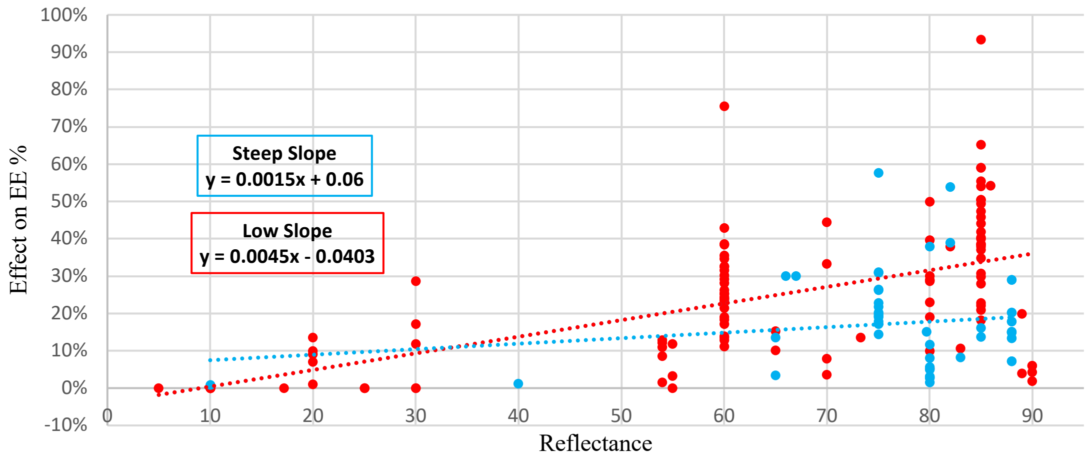

Figure 6: Effect of reflectance on energy efficiency for steep slope and low slope roofs

Figure 7 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.

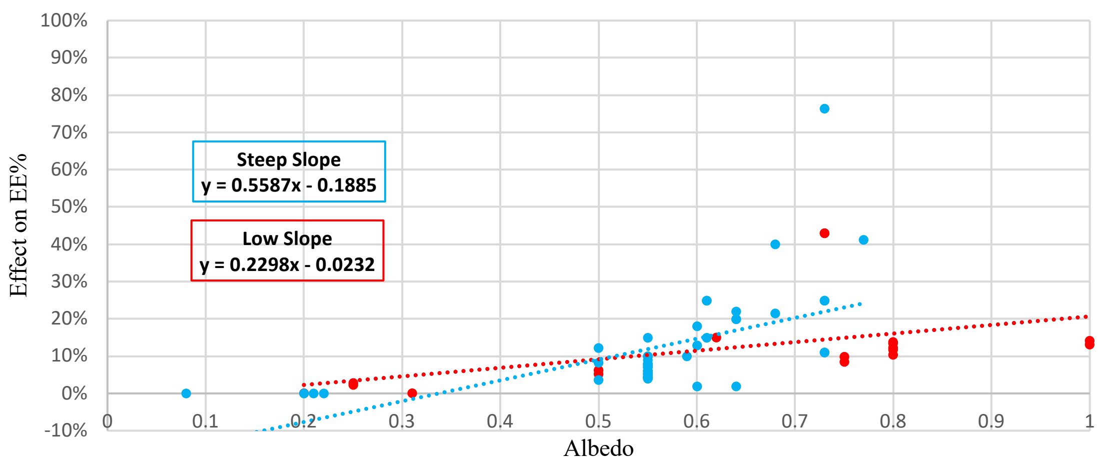

Figure 7: Effect of albedo on energy efficiency for steep slope and low slope roofs

Simulation vs Real-World

The data below show the effect of reflectance and albedo on the energy efficiency of a building for simulation and real-world-based studies. Energy efficiency is defined as the percentage change in energy usage of a standard roof and a roof system modification.

Table 7 presents the different types of roof system modifications for simulation and real-world studies. Out of a total of four-hundred sixty-nine (469) roof system modifications, four-hundred eleven (411) were modifications made for simulation-based studies, and fifty-eight (58) were modifications made for real-world-based studies. Modifications for simulation-based studies were further divided into three-hundred fifty-one (351) coating-based, fifty-four (54) insulation changes, and six (6) membrane-based modifications. Real-world-based studies were further divided into thirty-two (32) coating-based and twenty-six (26) membrane-based modifications.

Table 7: Roof system modifications for simulation and real-world studies

Type of Study	Roof System Modification	Sample size
Simulation	Coating - based	351
	Insulation change	54
	Membrane - based	6
Real-World	Coating - based	32
	Membrane - based	26
Total Roof System Modifications		**469**

The fifty-eight (58) simulation-based studies used nineteen (19) different simulation models and software’s for calculating the cool roof's effect on energy efficiency, as shown in Table 8. A diverse range of modeling approaches were employed to investigate energy efficiency. Energy Plus and DOE 2.1 were among the most commonly successfully applied simulation models.

Table 8: Types of simulation models

Type of Simulation model	No. of studies
Analytical Method	1
Autodesk Green Building Studio	1
Community Earth System Model	1
Complex Fast Fourier Transform	1
CoolCalkPeak	1
DOE 2.1	8
Energy Plus	21
Envi Met	2
HASP/ACLD-β	1
Heat Transfer Model	1
hygIRC-C	1
Integrated Environmental Solutions	2
Je Plus	1
MATLAB	1
MUKLIMO 3	1
STAR	2
THERB	1
Trnsys	7
WRF	4
Total	**58**

Figure 8 shows the effect of reflectance on energy efficiency for real-world and simulation-based studies. For every change in reflectance by 10 units, there is an increase in energy efficiency by 3% for real-world studies and 3% for simulation-based studies. Both real-world and simulation-based studies have a similar effect on energy efficiency with respect to reflectance.

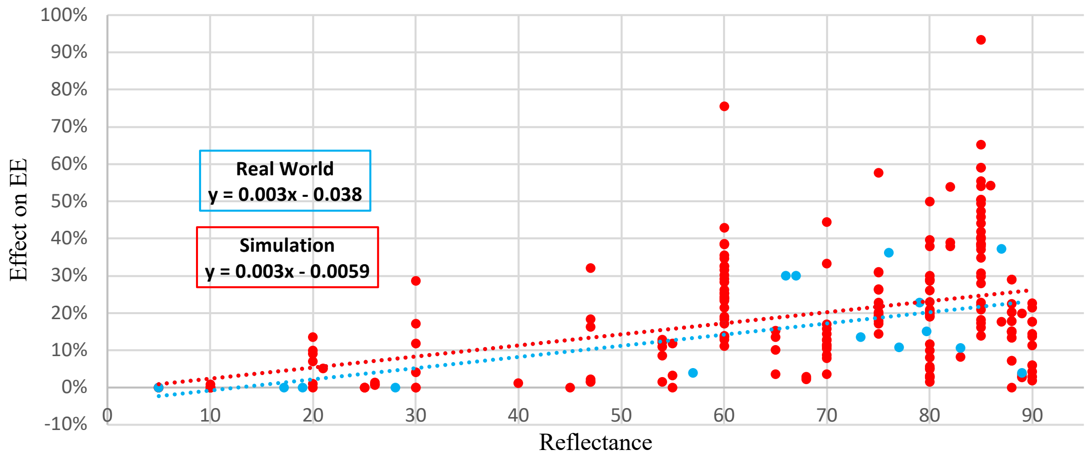

Figure 8: Effect of reflectance on energy efficiency for real-world and simulation-based studies

Figure 9 shows the effect of albedo on energy efficiency for real-world and simulation-based studies. For every change in albedo by 0.1 units, there is an increase in energy efficiency by 3.6% for real-world studies and 3.1% for simulation-based studies.

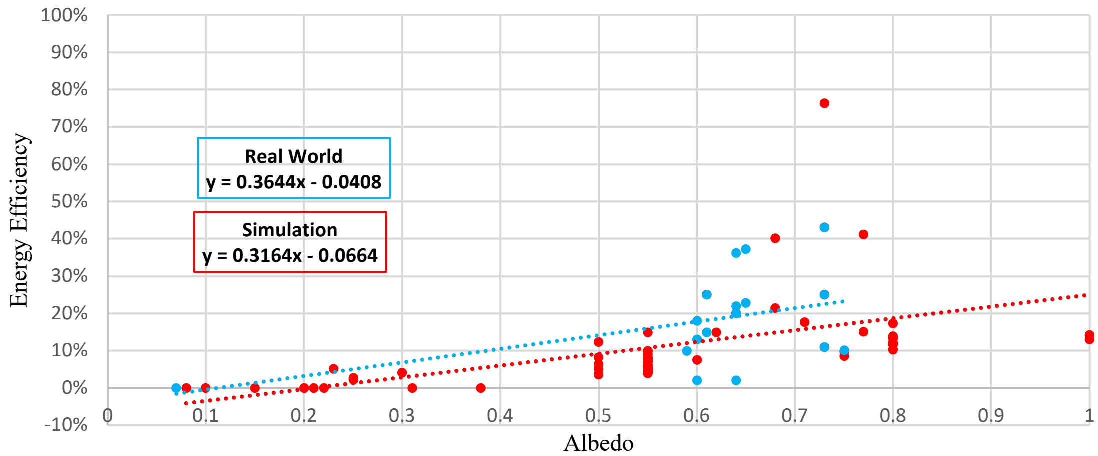

Figure 9: Effect of albedo on energy efficiency real-world and simulation-based studies

Synthesis and Analysis of Data

By analyzing the seventy-seven (77) studies, reflectance and albedo are identified as key parameters that affect energy efficiency of a building. They impact the amount of solar radiation absorbed and reflected by the roof and subsequently the building. However, there are various other parameters that also have a significant impact on energy efficiency. Some of the key parameters include location, age of roof, roof properties like albedo, reflectance, insulation, climate of the location, type of study etc., to calculate energy efficiency by changing the roof membrane. It was found that impact of reflectance, albedo and insulation on the energy efficiency of a building was dependent on the location and climate of a building. Data capture duration in the studies was not consistent and it was captured in different climates for durations that do not accurately represent the seasonal variations of the location. The type of studies, simulation or real-world had different effects on energy efficiency. To develop a framework for an ideal study, twelve (12) parameters were identified from these studies that affect the energy efficiency of a building when making changes on a roof. Each study analyzed few of these parameters but by taking the correct combination of parameters ideal for a study, the analysis can accurately represent the impact of cool roof on energy efficiency.

Table 9 presented here shows the inclusion of twelve (12) different parameters in seventy-seven (77) studies. Yes (Y) means the study included the factor in calculating energy efficiency, and No (N) means it did not. N/A represents simulation-based studies in which data was simulated for effect on energy efficiency for the whole year. The inclusion of these parameters in seventy-seven (77) studies is shown in Appendix C. Out of the seventy-seven (77) studies, fifty-eight (58) studies are simulation-based, followed by seventeen (17) real-world studies, and two (2) are literature-review-based studies. Reflectance and albedo are two key factors in studying cool roof materials. Reflectance is the capability of a surface to reflect solar radiation back into the environment, and albedo is the proportion of radiation reflected by a horizontal surface. Lighter-colored materials tend to have high solar reflectance and albedo values, while darker-colored materials have low values. However, both solar reflectance and albedo values can decrease with wear and tear, aging, soiling, and weatherability of the cool material (Romeo et al., 2013).

In the majority of the studies, change in reflectance is the primary factor considered while calculating the effect on the energy efficiency of a building. However, only a third of the studies have considered the effect of insulation and albedo in energy efficiency calculations. Insulation plays a crucial role in regulating heat transfer in and out of the building. It can either increase or decrease cooling and heating loads depending on the climate of a place. In hotter regions, it can increase the cooling load as it prevents the internal heat from dissipating. Whereas in colder regions, insulation can help decrease heating loads by slowing the heat from leaving the building.

A majority of the studies have considered the area of the roof when calculating the effect on energy efficiency. Another important consideration in evaluating the impact of cool materials on energy efficiency is the location and climate of a building. All the studies have taken into consideration the location of the building when calculating the effect on energy efficiency by either using a simulation model or a real-life experiment for a specific duration. It is important to consider the climate and seasonal changes in temperature throughout the year to evaluate the effect of cool materials on energy efficiency accurately. A majority of the studies have been conducted in hot weather conditions giving results only for cooling load reductions. Only fourteen (14) studies have considered both hot and cold weather to calculate the effect on cooling and heating loads. A majority of the simulation-based studies, calibrated the model using the data captured over a few days in different climates and extrapolated the energy efficiency over the whole year. While this approach can give a rough estimate of the reduction in energy consumption, it is not accurate considering the changes in temperature throughout the year.

Table 9: Inclusion of parameters in studies

	Avg. Sample Size	**Area of roof**	**Location**	**Color**	**Insulation**	**Reflectance**	**Albedo**	**Hot weather**	**Cold weather**	**Duration**	**Simulation**	**Real World**
Y	7.17	54	75	48	27	52	24	53	14	-	58	17
N		21	0	27	48	23	51	0	39	-	17	58
N/A		-	-	-	-	-	-	22	22	22	-	-

Survey

A survey was conducted with ten (10) industry professionals to understand their perception of the twelve (12) parameters identified in RO 2. There was a diverse range of respondents that represented different sectors of roofing industry in the country. To conduct the survey, fourteen (14) people were initially contacted and invited to participate in the study. However, four (4) people declined to take the survey as they felt they needed more expertise to provide informed opinions about this study. Among the survey respondents, two (2) were from the four (4) biggest roofing manufacturers in the country. In addition, the survey also included two (2) large roofing contractors that have extensive experience working on various roofing projects. A few of these respondents had an experience ranging from 35 – 40 years in the roofing industry. With their experience in roofing manufacturing and roofing projects, they have acquired extensive knowledge in the field and have also encountered various roofing materials, techniques and latest innovation in the industry. Finally, the survey also included respondents from the general contracting industry. Getting this perspective was helpful as they have a broad understanding of building construction and requirements for energy-efficient buildings. Overall, the survey had a broad range of respondents and their experience in the construction industry made them well-equipped to provide diverse perspectives for the relative importance of parameters affecting energy efficiency. The survey is in Appendix B. The survey asked the professionals to score the given parameters relative to the other parameters. The range of the scores was 1 – 5, with 1 indicating equal importance and 5 indicating extreme importance. Using AHP, each parameter was assigned a weight based on the relative importance to other parameters.

Table 10 shows the relative scores given to each parameter based on ten (10) survey responses.

Table 10: Pairwise comparison of parameters based on survey

	Location	Hot weather	Cold weather	Insulation	Albedo	Reflectance	Real-World study	Simulation-based study	Sample size	Duration of data capture	Color of roof	Area of roof
Location	1.00	0.28	0.26	0.29	1.01	0.65	0.43	1.36	0.47	0.63	0.50	0.48
Hot weather	3.60	1.00	0.37	0.48	0.52	0.34	0.41	0.94	0.43	0.43	0.31	0.54
Cold weather	3.80	2.72	1.00	0.25	0.72	0.66	0.43	0.94	0.41	0.48	0.56	0.54
Insulation	3.40	2.07	3.93	1.00	0.58	0.60	0.42	0.75	0.52	0.68	1.00	0.75
Albedo	0.99	1.93	1.39	1.73	1.00	0.43	0.40	0.72	0.45	0.56	0.32	0.60
Reflectance	1.53	2.93	1.52	1.67	2.33	1.00	0.44	0.75	0.52	0.47	0.32	0.52
Real-World study	2.33	2.47	2.33	2.40	2.52	2.27	1.00	1.59	0.63	0.52	0.32	0.43
Simulation-based study	0.73	1.07	1.07	1.33	1.39	1.33	0.63	1.00	0.38	0.47	0.54	0.69
Sample size	2.13	2.33	2.47	1.93	2.20	1.93	1.60	2.60	1.00	0.52	0.44	0.60
Duration of data capture	1.60	2.33	2.07	1.47	1.80	2.13	1.92	2.13	1.92	1.00	0.41	0.44
Color of roof	2.00	3.27	1.77	1.00	3.13	3.13	3.12	1.84	2.25	2.47	1.00	0.71
Area of roof	2.07	1.87	1.85	1.33	1.65	1.93	2.32	1.44	1.65	2.27	1.40	1.00
Total	25.19	24.26	20.03	14.90	18.86	16.41	13.11	16.06	10.63	10.49	7.12	7.32

Table 11 shows the normalized score of each parameter and indicates the weightage given to each one using AHP. Color and area of the roof are two parameters that have been given the maximum weightage. The color of the roof is an important parameter that affects the energy efficiency of a building. Lighter-colored roofs tend to reflect more light than darker-colored roofs, reducing the amount of heat that is absorbed by the roof and transferred inside the building. The wavelengths of light reflected by the surface of a roof determine the color of the roof. (Grzybowski et. al, 2019) Different colors absorb different wavelengths of light and reflect others. For e.g., a black roof absorbs the majority of the visible light, whereas a white roof reflects the majority of the visible light. Reflectance and albedo can both have an impact on the color of a roof as they control the amount of light absorbed and reflected by a surface. A surface with high reflectance and albedo will reflect more light and heat. According to the data collected, the color of the roof, reflectance, and albedo have a combined weightage of about 27%, making them the most important parameters to consider when calculating the energy efficiency of a cool roof.

The second most important parameter is the area of a roof when calculating the impact of the cool roof on energy efficiency. Larger roof areas, compared to smaller roof areas, will require more energy to heat or cool a building, which must be factored into energy saving calculations. In addition, the slope of a roof and presence of shading from nearby structures can also impact the overall savings.

Sample size and duration of data capture together hold a weightage of approximately 20%, making them important parameters to consider when determining energy efficiency. The number of roof system modifications studied on a standard roof is referred to as the sample size. A larger sample size will yield more reliable and representative results, indicating how cool roofs perform under various conditions.

The amount of time over which data is collected is referred to as the duration of data capture. The energy efficiency of a cool roof can change depending on the time of day and seasonal variations. Gathering data over an adequate time frame to capture these variations is essential. With a longer duration of data capture, the results are likely to be more accurate and will help assess variations in energy efficiency brought on by the change in weather patterns.

Real-world studies hold about 3% more importance than simulation-based studies. Energy monitoring systems are frequently used in real-world studies to track the actual energy usage of the building over time. On the other hand, simulation-based studies utilize computer models to simulate the energy efficiency of a building in various conditions. These models are used to estimate energy consumption based on design parameters like the orientation of a building, insulation, and the color of roof. However, these models are limited by the accuracy of input and assumptions and may not correctly represent the actual performance of the building. Simulation-based studies are helpful when the objective is to explore hypothetical scenarios or test the impact of different parameters on energy efficiency under controlled conditions. Real-world studies can offer a more precise evaluation of a building's energy efficiency and point out areas for improvement by directly measuring the energy consumption of a building in its actual operating conditions.

Conducting studies in cold weather conditions is about 2% more important than conducting studies in hot weather conditions. While cool roofs help reduce cooling load and heat gain during hot weather conditions, the "heat penalty" associated with cool roofs in the winter can offset some of these energy savings. This results from the increased heating demand, as cool roofs have high reflective properties. The location and orientation of a building, type of insulation, and effectiveness of the heating system are variables that can affect the heat penalty associated with cool roofs. According to the survey, insulation is given an importance of 8% when evaluating energy savings as it works differently in different weather conditions. Conducting experiments in cold weather conditions can provide a more accurate assessment of the potential net energy savings of a building. This will enable a more thorough evaluation of the performance of cool roofs and identify the optimal conditions in which a cool roof should be installed.

Table 11: Normalized scores and weights of each parameter

	Location	**Hot weather**	**Cold weather**	**Insulation**	**Albedo**	**Reflectance**	**Real-World study**	**Simulation-based study**	**Sample size**	**Duration of data**	**Color of roof**	**Area of roof**	**Mean**	**Weight (%)**
Location	0.040	0.011	0.013	0.020	0.054	0.040	0.033	0.085	0.044	0.060	0.070	0.066	0.045	**4.46**
Hot weather	0.143	0.041	0.018	0.032	0.027	0.021	0.031	0.058	0.040	0.041	0.043	0.073	0.047	**4.75**
Cold weather	0.151	0.112	0.050	0.017	0.038	0.040	0.033	0.058	0.038	0.046	0.079	0.074	0.061	**6.14**
Insulation	0.135	0.085	0.196	0.067	0.031	0.037	0.032	0.047	0.049	0.065	0.140	0.103	0.082	**8.22**
Albedo	0.039	0.080	0.069	0.116	0.053	0.026	0.030	0.045	0.043	0.053	0.045	0.083	0.057	**5.68**
Reflectance	0.061	0.121	0.076	0.112	0.124	0.061	0.034	0.047	0.049	0.045	0.045	0.071	0.070	**7.03**
Real-World study	0.093	0.102	0.116	0.161	0.134	0.138	0.076	0.099	0.059	0.050	0.045	0.059	0.094	**9.43**

Simulation-based study	0.029	0.044	0.053	0.089	0.074	0.081	0.048	0.062	0.036	0.045	0.076	0.095	0.061	**6.11**
Sample size	0.085	0.096	0.123	0.130	0.117	0.118	0.122	0.162	0.094	0.050	0.062	0.083	0.103	**10.34**
Duration of data capture	0.064	0.096	0.103	0.098	0.095	0.130	0.146	0.133	0.181	0.095	0.057	0.060	0.105	**10.49**
Color of roof	0.079	0.135	0.089	0.067	0.166	0.191	0.238	0.115	0.212	0.235	0.140	0.098	0.147	**14.71**
Area of roof	0.082	0.077	0.093	0.089	0.088	0.118	0.177	0.090	0.156	0.216	0.197	0.137	0.127	**12.65**

Table 12 shows the weights assigned to each parameter and the number of studies that included each parameter in calculating energy efficiency. The total number of studies are seventy-seven (77), of which two (2) are literature review studies not considered here. The color of the roof that is given maximum weightage is not accounted for in twenty-seven (27) studies. Albedo and reflectance that define the color of a roof are not used in fifty-one (51) and twenty-three (23) studies, respectively. The area of the roof is the next most important parameter, and twenty-one (21) studies did not factor it into calculations. As for the duration of data capture, twenty-two (22) studies did not have a duration for real data capture and used simulation models to calculate energy efficiency for the whole year. The majority of the studies did not consider data capture during cold weather and the application of insulation to reduce energy usage in a building. The table shows the areas of improvement while developing methodologies to conduct experiments and evaluate the effect of cool roof application. The use of real-world experiments in varying climatic conditions with different building typologies and range of albedo, reflectance, and insulation values is essential to build an ideal study framework.

Table 12: Weightage and inclusion of parameters in studies

Ranked by importance	Parameter	Weightage (%)	Parameter included in # of studies	Parameter not included in # of studies	N/A
# 1	**Color of roof**	14.71	48	27	
# 2	**Area of roof**	12.65	54	21	
# 3	**Duration of data capture**	10.49	53	-	22
# 4	**Sample size**	10.34	Average sample size 7.17		
# 5	**Real-World study**	9.43	17	58	
# 6	**Insulation**	8.22	27	48	
# 7	**Reflectance**	7.03	52	23	
# 8	**Cold weather**	6.14	14	39	22
# 9	**Simulation-based study**	6.11	58	17	
#10	**Albedo**	5.68	24	51	
#11	**Hot weather**	4.75	53	0	22
# 12	**Location**	4.46	75	0	

Table 13 shows codes given to different parameters to further do experiments by keeping some parameters constant (C) and some variable (V). By doing a controlled experiment, and manipulating one variable and keeping the other variables constant, it is possible to isolate the effects of individual components and better understand how they affect energy efficiency of a building. For e.g., a study wants to determine the effect of insulation on energy efficiency. If multiple parameters are varied simultaneously, it will be challenging to determine the changes observed due to isolation alone. However, if other parameters are kept constant and the study calculates the effect of insulation in different locations with varying climate conditions, it can help determine the changes in energy efficiency due to different insulation types and thicknesses. This can help identify cause-and-effect relationship between different parameters and develop a more accurate model to predict energy efficiency.

Table 13: Codes for different parameters

	Location	**Hot weather**	**Cold weather**	**Insulation**	**Albedo**	**Reflectance**	**Real-World study**	**Simulation-based study**	**Sample size**	**Duration of data capture**	**Color of roof**	**Area of roof**
Code	X1	X2	X3	X4	X5	X6	X7	X8	X9	X10	X11	X12

Following are examples of research questions to determine the effect of specific parameters by keeping a few constant and others varying with respect to the parameter in question.

1. Scenario 1 (Location)

   Study the effect of change in location for different albedo and reflectance values on energy efficiency of a building.

   Variable: X1, X2, X3, X5, X6, X11, X12

   Constant: X9, X10

2. Scenario 2 (Location)

   Study the effect of change in location for different insulation thicknesses on energy efficiency of a building.

   Variable: X1, X2, X3, X4, X11, X12

   Constant: X9, X10

3. Scenario 3 (Hot Weather)

Study the effect of hot weather conditions in various locations for different reflectance and albedo values on energy efficiency of a building.

Variable: X1, X2, X5, X6, X11, X12

Constant: X9, X10

4. Scenario 4 (Cold Weather)

   Study the effect of cold weather conditions in various locations for different reflectance and albedo values on energy efficiency of a building.

   Variable: X1, X3, X5, X6, X11, X12

   Constant: X9, X10

5. Scenario 5 (Insulation)

   Study the effect of different insulation thickness in one location for different weather conditions on energy efficiency of a building.

   Variable: X4, X12

   Constant: X1, X2, X3, X9, X10, X11

6. Scenario 6 (Insulation)

   Study the effect of different insulation thicknesses in various locations in different climates on energy efficiency of a building.

   Variable: X1, X2, X3, X4, X12

   Constant: X9, X10, X11

7. Scenario 7 (Albedo)

   Study the effect of different albedo values in one location for different building types and areas on energy efficiency of a building.

Variable: X5, X11, X12

Constant: X1, X2, X3, X9, X10

8. Scenario 8 (Albedo)

   Study the effect of different albedo values in various locations for different building types and areas on energy efficiency of a building.

   Variable: X1, X2, X3, X5, X11, X12

   Constant: X9, X10

9. Scenario 9 (Reflectance)

   Study the effect of different reflectance values in one location for different building types and areas on energy efficiency of a building.

   Variable: X6, X11, X12

   Constant: X1, X2, X3, X9, X10

10. Scenario 10 (Reflectance)

    Study the effect of different albedo values in various locations for different building types and areas on energy efficiency of a building.

    Variable: X1, X2, X3, X6, X11, X12

    Constant: X9, X10

11. Scenario 11 (Real-World study)

    Study the results of a real-world study for effect of change in albedo and reflectance values in one location.

    Variable: X5, X6, X11, X12

    Constant: X1, X2, X3, X9, X10

12. Scenario 12 (Simulation-based study)

    Study the results of a real-world study for effect of change in albedo and reflectance values in one location.

    Variable: X5, X6, X11, X12

    Constant: X1, X2, X3, X9, X10

13. Scenario 13 (Color of roof)

    Study the effect of color of roof in one location for different building types and areas on energy efficiency of a building.

    Variable: X5, X6, X11, X12

    Constant: X1, X2, X3, X9, X10

14. Scenario 14 (Area of roof)

    Study the effect of different building types and areas in one location for varying reflectance and albedo values on energy efficiency of a building.

    Variable: X5, X6, X11, X12

    Constant: X1, X2, X3, X9, X10

Table 14 shows methods in which each parameter can be tested in studies. It shows each parameter as a variable that can have different values, duration and climate.

Table 14: Methods to test different parameters

Parameter	**Type of tests**
Location	Test application of cool roofs in different locations with same, similar and different weather conditions.
Hot weather	Test application of cool roofs in hot weather conditions with and without insulation.
Cold weather	Test application of cool roofs in cold weather conditions with and without insulation.

Insulation	Test application of cool roofs with different thickness of insulation.
Albedo	Test cool roofs with different albedo values ranging from 0 – 1.
Reflectance	Test cool roofs with different reflectance values ranging from 0 – 100.
Real-World study	Test application of cool roofs in with experiments in real weather conditions in different locations.
Simulation-based study	Use real-world data gathered over a period of time that accounts for seasonal and weather changes to run simulation models.
Sample size	Test application of cool roofs with different permutations and combinations of insulation thickness, albedo and reflectance values in various locations and climates.
Duration of data capture	Capture real-world data with the application of cool roofs over a significant duration so it is representative of different weather conditions
Color of roof	Capture data of different albedo and reflectance values that represent different roof colors.
Area of roof	Capture data for the application of same cool roofs on different building typologies and area of roof.

Figure 10 shows the methodology for an ideal study while considering the parameters based on their order of importance. Based on the survey results and their comparison with the limitations of the studies, the five (5) most important parameters are the color of the roof, area of the roof, duration of data capture, sample size, and real-world study. The following methodology suggests identifying a range of colors for an experiment first. This also involves identifying a range of albedo and reflectance values for those colors. The next most important parameter is the area of the roof which consists in categorizing buildings into small, medium, and large building areas. The third most important parameter is the data capture duration, which includes conducting experiments in different weather conditions for a duration that correctly captures the seasonal variations. After this is the number of roofs to be selected for an experiment. This can include identifying a number of locations and building types to calculate a sample for the experiment. Real-world studies hold more importance than simulation-based studies.

Simulations can assist in determining the best combinations of these parameters for each building type and location, after which a real-world experiment can be conducted.

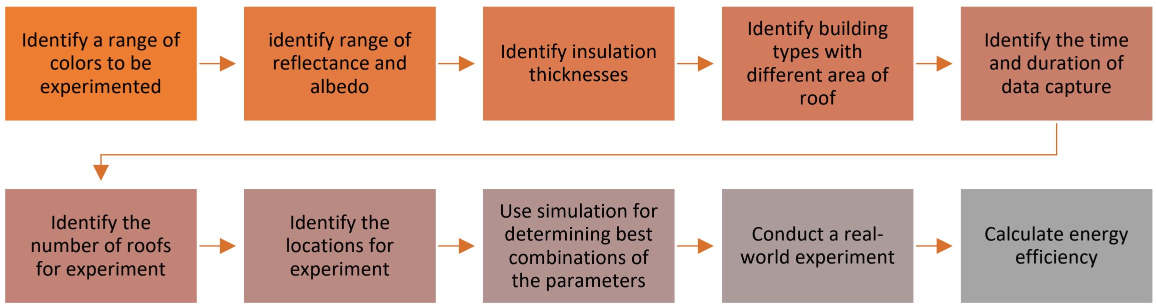

Figure 10: Ideal study methodology

Table 15 provides a comprehensive framework to conduct an ideal study for two (2) colors and three (3) building typologies. The research framework includes altering the standard roof with a roof system medication and comparing the energy usage of the standard and modified roof. Hypothetical scenarios can be explored using simulation models to determine the optimum reflectance, albedo, and insulation values for the modified roof systems. Real-world experiments will be carried out in both hot and cold weather conditions for a duration that is representative of varying weather conditions. In this example, two (2) colors of different albedo, reflectance, and insulation values are used to modify a standard roof in both weather conditions. The difference in energy usage of standard roof and roof system modification is used to calculate the effect on energy efficiency in each weather condition. This is further used to calculate net energy savings with the application of cool roofs throughout the year. This ideal framework currently considers parameters based on their overall importance from the results of the survey. However, in future ideal design, a more detailed analysis of each parameter is necessary.

Instead of looking at the parameters as a whole, there is a need to break down these parameters into components to provide a more granular look at each parameter. For e.g., defining the duration of data capture for a particular location in specific number of days, weeks or months would help in identifying how it impacts the overall energy efficiency and allow for more targeted improvements to the design framework.

Table 15: Ideal study framework

Building types (Area, Sample)		Building 1		Building 2		Building 3	
Standard roof		Standard roof energy usage – A kWh		Standard roof energy usage – B kWh		Standard roof energy usage – C kWh	
Explore hypothetical scenarios using simulation models (Simulation)							
Roof System Modification (Weather, Duration, Color, A, R, I)	Hot Weather	Color 1 (Albedo X1, Reflectance Y1, Insulation Z1)	Color 2 (Albedo X2, Reflectance Y2, Insulation Z2)	Color 1 (Albedo X1, Reflectance Y1, Insulation Z1)	Color 2 (Albedo X2, Reflectance Y2, Insulation Z2)	Color 1 (Albedo X1, Reflectance Y1, Insulation Z1)	Color 2 (Albedo X2, Reflectance Y2, Insulation Z2)
	Energy usage	A1	A2	B1	B2	C1	C2
	Increase or decrease	A - A1	A - A2	B - B1	B - B2	C - C1	C - C2
Roof System Modification (Weather, Duration, Color, A, R, I)	Cold Weather	Color 1 (Albedo X1, Reflectance Y1, Insulation Z1)	Color 2 (Albedo X2, Reflectance Y2, Insulation Z2)	Color 1 (Albedo X1, Reflectance Y1, Insulation Z1)	Color 2 (Albedo X2, Reflectance Y2, Insulation Z2)	Color 1 (Albedo X1, Reflectance Y1, Insulation Z1)	Color 2 (Albedo X2, Reflectance Y2, Insulation Z2)
	Energy usage	A11	A12	B11	B12	C11	C12
	Increase or decrease	A - A11	A - A12	B - B11	B - B12	C - C11	C - C12

CHAPTER FOUR

CONCLUSIONS

The design of a building's roof can significantly impact energy efficiency. To determine the optimal design for the effect of the color of the roof membrane on energy efficiency, a number of considerations need to be taken into account. This paper provides an overview of the last 25 years of studies and how reflectance and albedo affect the energy efficiency of a building. The effect of change in reflectance and albedo was identified from the existing literature to draw conclusions about its overall effect on energy efficiency in terms of energy usage reduction, dollar savings, and temperature reductions. The survey conducted among industry professionals validates the literature review results by giving maximum weightage to parameters that were not included in most of the studies. This shows that there is a gap in the study methodologies and the importance given to different parameters.

An increase in reflectance and albedo leads to an overall increase in the energy efficiency of a building. An increase in albedo and reflectance values significantly reduce the cooling load of a building. Studies have shown that increasing these values in hot, mild, and equatorial climate zones offers maximum energy efficiency. In colder climates, an increase in albedo and reflectance results in increased heating demand as it prevents heat from entering the building. The baseline value of energy usage and temperature are essential factors that help determine the percentage of savings. A lower baseline value may show 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.

Thermal insulation is another factor that plays a role in changing the energy efficiency of a building. In hot, mild, and equatorial climate zones, roofs with thermal insulation result in increased cooling demands as it prevents the dissipation of internal heat gains. In colder climates, the use of thermal insulation can decrease heating loads as the internal heat of the building will remain intact. A combination of a roof with high reflectance and thermal insulation is more effective in reducing thermal load than either higher reflectance roofing or insulation alone. Insulation plays a significant role in the effect of roofing membrane on heating demand.

In conclusion, evaluating the energy efficiency of a building requires consideration of various factors, including solar reflectance, thermal insulation, and baseline temperature values. A combination of highly reflectance roofing membrane and thermal insulation is most effective in reducing heating load, while the impact of reflectance of the roof is equally important in warm climates.

CHAPTER FIVE

LIMITATIONS

This report acknowledges several limitations with the help of a systematic literature review and a survey to validate the results of the inclusion of different parameters. There is a gap identified with the survey results that not all studies have considered parameters in their order of importance. A majority of the studies have yet to consider the most important parameters for evaluating energy efficiency of cool roofs. Most of the studies are simulation-based, which may only partially capture real-world conditions and do not consider seasonal variations. Additionally, many studies compare energy cost savings across different locations without normalizing the energy cost for that region, which can lead to misleading comparisons.

Furthermore, most of the studies have conducted experiments on the effect of the cool roof on energy savings during the summer months, representing only a portion of the year. Heat penalty with the application of a cool roof during the winter season is only sometimes clarified or considered in all studies. This limits the generalizability of the findings and may misrepresent the energy efficiency of cool roofs in different climates.

To determine annual roof performance, most studies used a short data capture duration during specific months. This may not give an accurate representation of the long-term impact of cool roofs on energy efficiency, and additional research is required to fully understand cool roof annual performance.

CHAPTER FIVE

FUTURE PATH

A change in the design of a building's roof, such as changing the albedo and reflectance, can affect the energy efficiency of the building. Many variables need to be taken into account in order to investigate this effect on energy efficiency. Several studies have concentrated on the change in albedo and reflectance caused by painting the roof, installing a roofing membrane, or adding insulation. The percentage change in energy usage for a standard and the modified roof was used to calculate the impact on energy efficiency. The studies compared this modification for different locations and climates without accounting for the fact that the base case for energy usage in each location is different. Studies on the impact of changing climate on energy efficiency in relation to various roof modifications such as color, product type, insulation, and so on are required. This will provide valuable insight into effective ways to modify a roof for maximum energy savings while also considering the climate and location of the building.

A life-cycle analysis is also required to calculate energy savings in dollars over the life of a roof. This cost-benefit analysis will aid in selecting the most energy-efficient roofing materials and designs. It is also critical to assess the optimal cold vs. warm month ratio on annual energy efficiency due to various roof modifications. Building owners and managers can determine the most effective roof modifications based on the local climate.

Another important factor to consider is the cool material's aging, soiling, and weatherability throughout the building's lifespan. A roof membrane's reflectance and albedo tend to decrease with age and regular wear and tear. Previously, studies did not take these factors into account, which can lead to inaccurate conclusions about the effectiveness of various roofing materials and designs.

The impact of multiple cool roofs on local air temperatures and rooftop cooling on street-level air temperatures has yet to be determined. This is an important factor to consider because it can help determine the potential impact of widespread cool roof adoption on a larger scale.

A thorough and comprehensive study of the effect of membrane color in roof design on energy efficiency is required. This should consider various factors, such as the local climate, energy savings over the roof's life, the aging and weatherability of roofing materials, and the impact on local air temperatures. With proper analysis and design, it is possible to create roofs that provide energy savings, increase occupant comfort, and reduce the overall environmental impact of buildings.

APPENDICES

Appendix A

Definition of Study Design Parameters

Location	This is the physical location of a building in terms of continent, country, state, city, etc.,
Hot weather	The effect of cool roof on energy efficiency during hot weather.
Cold weather	The effect of cool roof on energy efficiency during cold weather.
Insulation	The effect of adding insulation on energy efficiency.
Albedo	This is a numerical way to define a cool roof. Albedo defines the whiteness of a roof. It ranges from a value of 0 to 1, 0 being the darkest roof and 1 being the lightest roof. This factor accounts for the effect on energy efficiency when the albedo of a roof is modified (increased) from that of a standard roof.
Reflectance	This is a numerical way to define a cool roof. Reflectance defines the amount of white light reflected from a roof. It ranges from a value of 0 to 100, 0 being the roof that reflects minimum light and 100 being the roof that reflects the maximum amount of light. (Note: Reflecting maximum light means that less heat is absorbed in the building) This factor accounts for the effect on energy efficiency when the reflectance of a roof is modified (increased) from that of a standard roof.
Real-World	This means that the study in question is a real-world based study that uses actual data from experiments in the location and draws conclusions based on these experiments.
Simulation	This means that the study in question is a simulation-based study that uses a simulation model calibrated to the location. The conclusions are drawn based on minimal real data capture and rely more on simulation.
Area of roof	The area of the roof that is used to calculate the energy efficiency of a building.
Color of roof	Color of the roof with respect to the albedo and reflectance of the membrane.
Sample Size	This number shows the number of roofs or locations studied in the research paper. For e.g., in a research paper that studies 10 roofs in 10 different locations worldwide, the sample size will be 100.
Data capture duration	This is the duration that data was captured to draw conclusions about the effect of different factors on energy efficiency. For Real-world studies, this is the number of days data was captured, and conclusions are drawn, whereas, for Simulation studies, data was captured for calibration and extrapolated to a few months or the whole year.

Appendix B

Survey for Pairwise Comparison

The goal of this survey is to understand your perception regarding the twelve (12) key factors that affect the energy efficiency of a building. We would appreciate your time in contributing to this study. This survey should take about five (5) minutes to complete. Your responses will be kept confidential and anonymous. Please reach out to adua@clemson.edu for any questions.

The twelve (12) factors that you will be asked about are listed below with definitions. Please keep these definitions in mind when answering the questions.

Location	Physical location of a building in terms of continent, country, state, city, etc.,
Hot Weather	The effect of cool roof on energy efficiency during hot weather.
Cold Weather	The effect of cool roof on energy efficiency during cold weather.
Insulation	The effect of adding insulation on energy efficiency.
Albedo	This is a numerical way to define a cool roof. Albedo defines the whiteness of a roof.
Reflectance	This is a numerical way to define a cool roof. Reflectance defines the amount of white light reflected from a roof.
Real - World	Data captured from real-world experiments.
Simulation	Data captured from simulation models.
Sample size	Number of roofs studied. For e.g., in a research paper that studies 10 roofs in 10 different locations worldwide, the sample size will be 100.
Duration of data capture	Number of days data was captured to draw conclusions. For Real-world studies, this is the number of days data was captured, and conclusions are drawn, whereas, for Simulation studies, data was captured for calibration and extrapolated to a few months or the whole year.
Color of roof	Color of the roof with respect to the albedo and reflectance of the membrane.
Area of roof	The area of the roof that is used to calculate the energy efficiency of a building.

Q1. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **the location of a roof**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Hot weather	○	○	○	○	○
Cold weather	○	○	○	○	○
Insulation	○	○	○	○	○
Albedo	○	○	○	○	○
Reflectance	○	○	○	○	○
Real-World study	○	○	○	○	○
Simulation-based study	○	○	○	○	○
Sample size	○	○	○	○	○
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q2. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **hot weather**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Cold weather	○	○	○	○	○
Insulation	○	○	○	○	○
Albedo	○	○	○	○	○
Reflectance	○	○	○	○	○
Real-World study	○	○	○	○	○
Simulation-based study	○	○	○	○	○
Sample size	○	○	○	○	○
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q3. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **cold weather**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Insulation	○	○	○	○	○
Albedo	○	○	○	○	○
Reflectance	○	○	○	○	○
Real-World study	○	○	○	○	○
Simulation-based study	○	○	○	○	○
Sample size	○	○	○	○	○
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q4. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **insulation**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Albedo	○	○	○	○	○
Reflectance	○	○	○	○	○
Real-World study	○	○	○	○	○
Simulation-based study	○	○	○	○	○
Sample size	○	○	○	○	○
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q4. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **albedo**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Reflectance	○	○	○	○	○
Real-World study	○	○	○	○	○
Simulation-based study	○	○	○	○	○
Sample size	○	○	○	○	○
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q5. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **reflectance**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Real-World study	○	○	○	○	○
Simulation-based study	○	○	○	○	○
Sample size	○	○	○	○	○
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q6. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **real-world study**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Simulation-based study	○	○	○	○	○
Sample size	○	○	○	○	○
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q7. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **simulation-based study**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Sample size	○	○	○	○	○
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q7. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **sample size**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Duration of data capture	○	○	○	○	○
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q7. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **duration of data capture**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Color of roof	○	○	○	○	○
Area of roof	○	○	○	○	○

Q7. For each factor listed below, please identify its relative importance on the energy efficiency of a building when compared to **color of roof**.

	Far less important	Slightly less important	Equally important	Moderately more important	Strongly more important
Area of roof	○	○	○	○	○

Appendix C

Inclusion of Study Design Parameters in 77 studies

	Sample Size	Area of roof	Location	Color	Insulation	Reflectance	Albedo	Hot weather	Cold weather	Duration	Simulation	Real World
1	6	Y	Y	Y	Y	Y	N	Y	Y	750 - 800	Y	N
2	5	Y	Y	Y	Y	N	N	N/A	N/A	N/A	Y	N
3	4	N	Y	N	Y	N	N	N/A	N/A	N/A	Y	N
4	5	Y	Y	N	Y	Y	Y	Y	N	1 - 10	Y	N
5	2	N	Y	N	N	Y	Y	Y	N	1 - 10	Y	N
6	2	N	Y	Y	N	Y	N	Y	Y	150 - 200	N	Y
7	1	Y	Y	Y	Y	Y	N	Y	Y	200 - 250	Y	N
8	3	Y	Y	Y	N	Y	N	Y	N	150 - 200	Y	N
9	2	Y	Y	Y	N	Y	N	Y	N	1 - 10	Y	N
10	3	Y	Y	Y	N	Y	N	Y	N	50 - 100	Y	N
11	6	Y	Y	Y	N	Y	N	Y	N	1 - 10	Y	N
12	2	Y	Y	Y	Y	N	Y	Y	N	100 - 150	Y	N
13	4	N	Y	N	N	Y	N	Y	N	1 - 10	Y	N
14	6	Y	Y	N	Y	Y	N	Y	N	1 - 10	Y	N
15	2	Y	Y	Y	Y	Y	N	Y	N	50 - 100	Y	N
16	15	N	Y	N	Y	Y	N	Y	N	1 - 10	Y	N
17	2	Y	Y	Y	N	N	Y	Y	N	10 - 50	N	Y
18	2	Y	Y	Y	N	Y	N	Y	N	10 - 50	N	Y
19	2	N	Y	N	N	Y	N	Y	N	100 - 150	Y	N
20	2	Y	Y	Y	N	Y	N	Y	Y	365	N	Y
21	6	Y	Y	Y	N	Y	N	Y	N	1 - 10	N	Y
22	4	Y	Y	N	Y	Y	N	Y	N	10 - 50	Y	N
23	3	Y	Y	N	N	Y	N	N/A	N/A	N/A	Y	N
24	8	Y	Y	Y	Y	Y	N	Y	N	10 - 50	Y	N
25	1	N	Y	N	N	Y	N	Y	N	1 - 10	Y	N
26	4	Y	Y	Y	N	N	Y	Y	N	1 - 10	N	Y
27	1	N	Y	N	N	N	Y	Y	N	1 - 10	Y	N
28	12	Y	Y	Y	Y	Y	N	N/A	N/A	N/A	Y	N
29	7	Y	Y	Y	Y	Y	N	Y	Y	250 - 300	Y	N
30	13	Y	Y	Y	Y	Y	N	Y	Y	250 - 300	Y	N
31	10	N	Y	Y	N	Y	N	Y	Y	1 - 10	Y	N
32	54	Y	Y	N	N	Y	N	N/A	N/A	N/A	Y	N

	Sample Size	Area of roof	Location	Color	Insulation	Reflectance	Albedo	Hot weather	Cold weather	Duration	Simulation	Real World
33	2	N	Y	N	N	Y	N	Y	N	1 - 10	Y	N
34	7	N	Y	Y	Y	Y	N	N/A	N/A	N/A	Y	N
35	2	Y	Y	Y	Y	Y	N	Y	N	10 - 50	N	Y
36	6	Y	Y	N	N	Y	N	N/A	N/A	N/A	Y	N
37	3	Y	Y	Y	N	Y	N	Y	Y	100 - 150	Y	N
38	2	Y	Y	Y	N	Y	N	Y	Y	100 - 150	Y	N
39	8	N	Y	Y	Y	Y	N	N/A	N/A	N/A	Y	N
40	3	N	Y	Y	N	Y	Y	Y	N	1 - 10	N	Y
41	3	Y	Y	Y	N	Y	N	N/A	N/A	N/A	Y	N
42	8	N	Y	N	N	N	Y	Y	N	1 - 10	Y	N
43	5	N	Y	Y	Y	N	N	Y	N	1 - 10	N	Y
44	3	Y	Y	N	N	Y	N	N/A	N/A	N/A	Y	N
45	Literature Review											
46	20	Y	Y	N	Y	Y	Y	N/A	N/A	N/A	Y	N
47	Literature Review											
48	1	Y	Y	Y	Y	N	Y	Y	N	10 - 50	Y	N
49	1	Y	Y	Y	N	N	Y	Y	N	50 - 100	Y	N
50	1	N	Y	N	N	N	Y	N/A	N/A	N/A	Y	N
51	7	Y	Y	Y	N	Y	N	Y	N	1 - 10	Y	N
52	2	Y	Y	Y	N	Y	N	N/A	N/A	N/A	Y	N
53	1	Y	Y	Y	N	Y	N	N/A	N/A	N/A	Y	N
54	2	Y	Y	Y	N	Y	N	Y	N	100 - 150	N	Y
55	1	Y	Y	Y	N	Y	N	N/A	N/A	N/A	Y	N
56	2	N	Y	N	N	N	Y	Y	N	50 - 100	Y	N
57	1	Y	Y	N	N	Y	N	N/A	N/A	N/A	Y	N
58	5	Y	Y	Y	Y	N	Y	Y	N	1 - 10	Y	N
59	12	N	Y	N	N	N	Y	Y	N	1 - 10	Y	N
60	22	Y	Y	Y	N	N	Y	N/A	N/A	N/A	Y	N
61	2	Y	Y	Y	N	N	Y	Y	N	50 - 100	Y	N
62	2	Y	Y	Y	Y	N	Y	Y	Y	150 - 200	Y	N
63	3	Y	Y	N	Y	N	Y	Y	Y	200 - 250	Y	N
64	9	Y	Y	N	Y	N	Y	Y	N	1 - 10	N	Y
65	14	Y	Y	Y	N	Y	N	Y	N	50 - 100	Y	N
66	3	Y	Y	N	Y	N	Y	Y	N	100 - 150	N	Y
67	20	Y	Y	Y	N	Y	N	Y	N	1 - 10	N	Y
68	48	Y	Y	Y	Y	Y	N	N/A	N/A	N/A	Y	N

	Sample Size	Area of roof	Location	Color	Insulation	Reflectance	Albedo	Hot weather	Cold weather	Duration	Simulation	Real World
69	13	Y	Y	Y	N	Y	N	N/A	N/A	N/A	Y	N
70	4	N	Y	Y	Y	N	Y	Y	Y	1 - 10	N	Y
71	22	Y	Y	Y	N	Y	N	N/A	N/A	N/A	Y	N
72	51	N	Y	Y	N	N	Y	N/A	N/A	N/A	Y	N
73	12	Y	Y	Y	N	Y	N	N/A	N/A	N/A	Y	N
74	2	Y	Y	Y	N	Y	N	Y	Y	500 - 550	N	Y
75	2	N	Y	N	N	Y	N	Y	Y	50 - 100	N	Y
76	1	Y	Y	N	N	Y	N	Y	N	1 - 10	N	Y
77	1	Y	Y	N	N	N	Y	Y	N	1 - 10	Y	N
Y		54	75	48	27	52	24	53	14	-	58	17
N		21	0	27	48	23	51	0	39	-	17	58
N/A		-	-	-	-	-	-	22	22	22	-	-

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