SHINE ON

Increasing Local Solar Reflectance as a Means to Reduce the Greenhouse Effect

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KEY CONCLUSIONS

1. **Increasing the solar reflectance of roofs, walls, and pavements reduces the Earth's energy imbalance and can significantly contribute to efforts to curb climate change. Yet, this unique benefit has not been recognized or valued in policymaking and investment decisions.**
2. **Managing the solar reflectance of the built environment immediately reduces local surface temperatures and the global energy imbalance and can be done in parallel with vital mitigation actions to reduce and remove greenhouse gas emissions.**
3. **A well-established body of research spanning 25 years allows us to value the impact of projects that increase solar reflectance in a similar way that governments and markets currently value projects that mitigate greenhouse gas emissions, potentially unlocking opportunities for supportive policy and investment.**
4. **Additional research is needed to refine models that provide a more comprehensive understanding of how surface reflectance and its effects change over time.**

EXECUTIVE SUMMARY

NASA's Goddard Institute for Space Studies found 2023 to be the hottest year since the late 19th century when climatic conditions were first systematically recorded, and noted that these conditions are "driven primarily by our fossil fuel emissions, and we're seeing the impacts in heat waves, intense rainfall, and coastal flooding."[1] Average temperatures are rising, and current urbanization trends are exposing billions of people to dangerously hot weather. Extreme heat negatively affects nearly every aspect of human life, from our health to the resilience of the systems and infrastructure we rely on to survive and thrive.

Dark-colored, impermeable products, such as asphaltic roads and roofing materials, cover much of our built environment. These surfaces absorb more sunlight than the natural surfaces they replaced and thus emit more longwave radiation that warms people, buildings, cities, and the planet.[2] Increasing the solar reflectance, or albedo, of our built environment is a strategy to mitigate the heat created by these surfaces. At scale, deploying higher-albedo surfaces also has a global effect by reflecting more sunlight into space and reducing the amount of emitted longwave radiation that gets trapped in the Earth's system. Increasing the ability of buildings and pavements to reflect more of the sun's energy and expanding shaded and vegetated areas have long been strategies to cool indoor and outdoor air and surface temperatures. There are many high-albedo materials available today to support a wide variety of appropriate use cases and conditions.

This white paper highlights a unique benefit of installing high-albedo surfaces: their ability to modify the Earth's energy balance to offset global warming. The Earth's energy (im)balance is the result of a complex set of interactions between the Earth and sunlight, known as radiative forcing. Incoming shortwave solar radiation (i.e., sunlight) may be reflected by the Earth's surface or absorbed and re-emitted as longwave radiation.[3] Increasing the solar reflectance of a surface in the built environment increases the ability of the Earth to reflect solar radiation and reduces the amount of the sun's energy that is absorbed and converted to heat.

Global implementation of high-albedo surfaces (e.g., cool roofs, walls, and pavements) has been slow, and much of their benefit is unrealized. A primary driver of this lack of scaled implementation is that climate finance, regulatory, and policy stakeholders narrowly focus on the value derived from improved energy efficiency from high-albedo surfaces rather than taking a more holistic view. The current approaches to financing and regulating high-albedo surfaces ignore that increasing the solar reflectance of a surface improves the Earth's energy balance, creating a cooling effect that counteracts the warming impact of greenhouse gases (GHGs) already in our atmosphere.

Research over the last 25 years permits a quantitative comparison of the effect of increasing the albedo of the built environment and the impact of GHG mitigation efforts. The radiative forcing of different GHGs are commonly compared to each other using a scaling factor called global warming potential (GWP). GWP is a ratio of how much energy a GHG will absorb compared to CO_2 over a given timeframe. Governments, capital markets, and other stakeholders use GWP to evaluate policies and investment opportunities. Likewise, researchers also use GWP as a measure to express the radiative forcing effect of albedo change in terms equivalent to CO_2 emissions.

This paper describes the science behind the beneficial effects of higher albedo surfaces on the Earth's energy balance and details six readily implementable policy pathways for accelerating the deployment of albedo-increasing projects:

- Research support
- Building and zoning codes
- Construction standards for facilities and infrastructure
- Albedo-based offsets in GHG regulatory systems
- Stipulations on government funding
- Large-scale pilot projects

The paper also explores the potential for market-based mechanisms, such as voluntary offsets and green finance, to attract private capital to accelerate the deployment of albedo projects, particularly to benefit communities that cannot invest in these projects. Finally, it identifies both technical and policy-related questions that deserve further exploration.

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GLOSSARY

Additionality – A requirement for carbon offset projects that GHG emissions after a project are lower than those that would have occurred in the most plausible alternative scenario. In other words, the GHG reductions occurred because of the offset activity and are above and beyond business-as-usual practices. The requirement to demonstrate additionality provides a fundamental condition for determining a project's eligibility for offsets.

Aerosols – Minute particles suspended in the atmosphere. Aerosols can scatter and absorb sunlight.

Albedo – The fraction of incident sunlight that is reflected by a surface, expressed as a value ranging from 0 or 0% (no reflectance) to 1 or 100% (perfect reflectance). Also known as solar reflectance.

Albedo (Terrestrial) – Albedo measured at the Earth's surface, excluding the effect of atmospheric absorption and reflection of sunlight.

Albedo (Top of Atmosphere) – Albedo measured at the top of the atmosphere where the absorption and reflection of the atmosphere (including clouds) affect the value.

Albedo-based offsets or credits – Offsets or credits originating from an albedo-increasing project that results in a reduction in global warming that is equivalent to that of an emissions-based carbon offset or credit.

Albedo Management of the Built Environment (AMBE) – Efforts that increase and maintain the surface albedo of man-made infrastructure such as roofs, walls, and pavements in both rural and urban contexts. AMBE is distinct from other approaches to increase albedo, such as large-scale surface albedo modification and atmospheric albedo management strategies. See also Surface Albedo Management of the Built Environment.

Anthropogenic – Resulting from or produced by human activities.

Building heat gain – Heat build-up inside of a structure that is caused by direct solar radiation, heat transferred from the exterior of the building, infiltration of outside warm air or loss of cool air indoors, and heat generated by people and equipment inside the building.

Carbon dioxide – A gas produced by burning carbon and organic compounds and by respiration. It is the most common anthropogenic greenhouse gas.

Carbon dioxide–equivalent (CO_2e) – The mass of carbon dioxide causing the same radiative forcing as some other factor of global warming such as methane or surface albedo modification.

Climate finance – Funding mechanisms that put a monetary value on carbon emissions, allowing entities to offset their greenhouse gas emissions by purchasing carbon credits from projects that reduce or remove carbon from the atmosphere.

Co-benefit – Any benefit of albedo management that does not reduce radiative forcing such as energy efficiency gains or improved thermal comfort.

Emissions-based carbon offset – A carbon offset that originates from a project that reduces emissions of CO_2e or other greenhouse gases.

Feedback effects – Responses to climate processes that either amplify or diminish the initial impact of a climate forcing, such as warming or cooling. These effects occur after an initial change in the climate and can either intensify (positive feedback) or reduce (negative feedback) the severity of the initial change, influencing the overall stability of the climate system. Examples of feedback effects include cloud formation and reduced surface albedo.

Flux – The rate of flow or continuous movement of a substance or property through a defined area. In physics, flux can refer to the magnitude and direction of the flow. Radiative flux is often measured in watts per square meter (W/m^2).

Geoengineering – Attempts to remedy global warming by altering radiative forcing worldwide through mechanisms other than GHG emissions avoidance or GHG sequestration in vegetation.

Greenhouse gas (GHG) – Any component in the Earth's atmosphere that absorbs and emits radiant energy, thus trapping heat, raising surface temperatures, and contributing to global warming. The most common greenhouse gases include water vapor, carbon dioxide, methane, nitrous oxide, ozone, and fluorinated gases.

Global cooling effect – A phenomenon in which increases in surface albedo or other feedback effects reduce global air and surface temperatures. Outside of the context of this paper, global cooling also refers to a hypothesis popular in the 1970s that suggested the Earth's temperature would decrease, potentially leading to an extended period of glaciation or an ice age. Improved data and climate models showed that the warming effect of greenhouse gases was the dominant force over factors contributing to cooler global temperatures, leading scientists to largely dismiss the global cooling hypothesis.

Global warming potential (GWP) – A unitless scaling factor equal to the ratio of the radiative forcing of one kilogram of a GHG to the radiative forcing of one kilogram of carbon dioxide.

Global warming potential of albedo (GWP_A) – Negative radiative forcing of increasing the albedo of one square meter of the Earth's surface by one percentage point (0.01) compared to the positive radiative forcing of emitting one kilogram of carbon dioxide. Units are kilograms per square meter.

Infrared radiation – Electromagnetic radiation with wavelengths longer than those of visible light and shorter than radio waves, and therefore invisible to the human eye. The infrared portion of the electromagnetic spectrum includes both longer-wavelength thermal infrared emitted from terrestrial sources and shorter-wavelength near-infrared originating from the sun.

Longwave radiation – A synonym for thermal infrared radiation.

Metric ton (or tonne) – 1,000 kilograms.

Near-infrared radiation – The infrared component of sunlight (spectrum 0.7–2.5 micrometers [µm]). This radiation travels at wavelengths too long for the human eye to see.

Point – A single unit of change. In this case, a unit of change in albedo or solar reflectance, equal to 1% (one percentage point) or 0.01 of the range from 0 or 0% (no reflectance) to 1 or 100% (perfect reflectance).

Radiative forcing – Net increase in energy flux in the atmosphere. Radiative forcing can be caused by natural or anthropogenic climate change factors. Anthropogenic radiative forcing is typically measured relative to the year 1750, which corresponds to the beginning of the industrial revolution.

Radiative imbalance – Difference between radiative energy flux arriving and leaving the Earth at the top of the atmosphere. Radiative imbalance is not equal to radiative forcing due to the Earth's other feedback effects.

Scope 1 – Of a GHG emissions inventory, those GHGs emitted from property owned or controlled by the inventorying entity.

Scope 2 – Of a GHG emissions inventory, those GHGs emitted from energy-generating equipment controlled by a party other than the inventorying entity but supplying energy to the entity. Usually, these are the emissions associated with the consumption of electricity from an offsite utility.

Sequestration-based offset – An offset that originates from a project that increases the sequestration of carbon or other greenhouse gas over the long term

Shortwave radiation – Energy emitted by the sun, or sunlight, typically between 300 and 2,500 nanometers (nm) in wavelength. Shortwave radiation includes ultraviolet radiation (between 300 and 400 nm), visible light (between 400 and 700 nm) and near infrared radiation (between 700 and 2500 nm).

Solar reflectance (SR) – The fraction of incident sunlight that is reflected by a surface, expressed as a value ranging from 0 or 0% (no reflectance) to 1 or 100% (perfect reflectance). Also known as albedo.

Solar absorptance – Solar absorptance is the fraction of solar radiation that an incident surface absorbs. Solar absorptance is a fractional value ranging from 0 (no absorptance) to 1 or 100% (perfect absorptance).

Surface Albedo Management of the Built Environment (AMBE) – See AMBE above.

Thermal infrared radiation – Infrared radiation emitted by a surface near a temperature of 300 Kelvin (80 °F or 27 °C) on a spectrum between approximately 4,000 – 80,000 nm.

Time horizon – The timespan over which GWP is integrated to calculate CO_2e.

United Nations Intergovernmental Panel on Climate Change SSP1-1.9 scenario – The IPCC's SSP1-1.9 GHG scenario is a very low greenhouse gas emissions scenario that starts in 2015 and declines to net zero around or after 2050, followed by varying levels of net negative CO_2 emissions. This scenario is designed to limit global warming to 1.5 °C above pre-industrial levels, which is the target set by the Paris Agreement.

Urban heat island (UHI) – A local elevation of ambient air temperature due to urban infrastructure, a lack of vegetated cover relative to rural areas, and sources of anthropogenic heat, such as vehicles.

Urban heat island effect (UHIE) – The difference between either air temperatures in an urban area compared to air temperatures outside an urban area.

Watt – A unit of power or rate of energy delivery equal to one joule per second.

THE EARTH'S ENERGY IMBALANCE

The Earth's climate is changing at an unprecedented rate. June 2024 marked the twelfth consecutive month in which global temperatures have exceeded pre-Industrial levels by more than 1.5 °C.[4] To understand climate change and how it is exacerbated or mitigated, we must consider the Earth's energy imbalance – the difference between how much energy the Earth receives from the sun and how much it re-emits into space.

The Earth's energy imbalance is the cause of global climate change. Anthropogenic greenhouse gas emissions and the expansion of our built environment that replaces natural space with dark, impermeable surfaces drive the energy imbalance. Sunlight (solar radiation) arrives at the Earth in spectrum 300 - 2500 nanometers (nm). Of this, about 40–45% of sunlight that arrives at the Earth's surface is visible to the human eye at wavelengths between 400 – 700 nm. Over half of the sunlight arrives in the near-infrared spectrum (wavelengths between 700 – 2,500 nm), invisible to the human eye. The remainder, about 5%, arrives in the ultraviolet spectrum (wavelengths between 300 – 400 nm).

Figure 1 illustrates the Earth's energy balance using 100 units of the sun's energy as a baseline. Shortwave radiation (sunlight) is represented by the blue arrows. Red arrows indicate energy flux within the atmosphere itself. Yellow arrows indicate energy flux at the Earth's surface.

Energy flux at the top of the atmosphere: One hundred units of sunlight (also known as solar radiation or shortwave radiation) from the sun enter the Earth's system at the top of the atmosphere. Some of this sunlight is reflected back into space by clouds and aerosols in the atmosphere (23 units of energy) and the Earth's surface (7 units of energy). The remaining sunlight (70 units of energy) is absorbed and re-emitted as thermal infrared radiation (also known as longwave radiation).

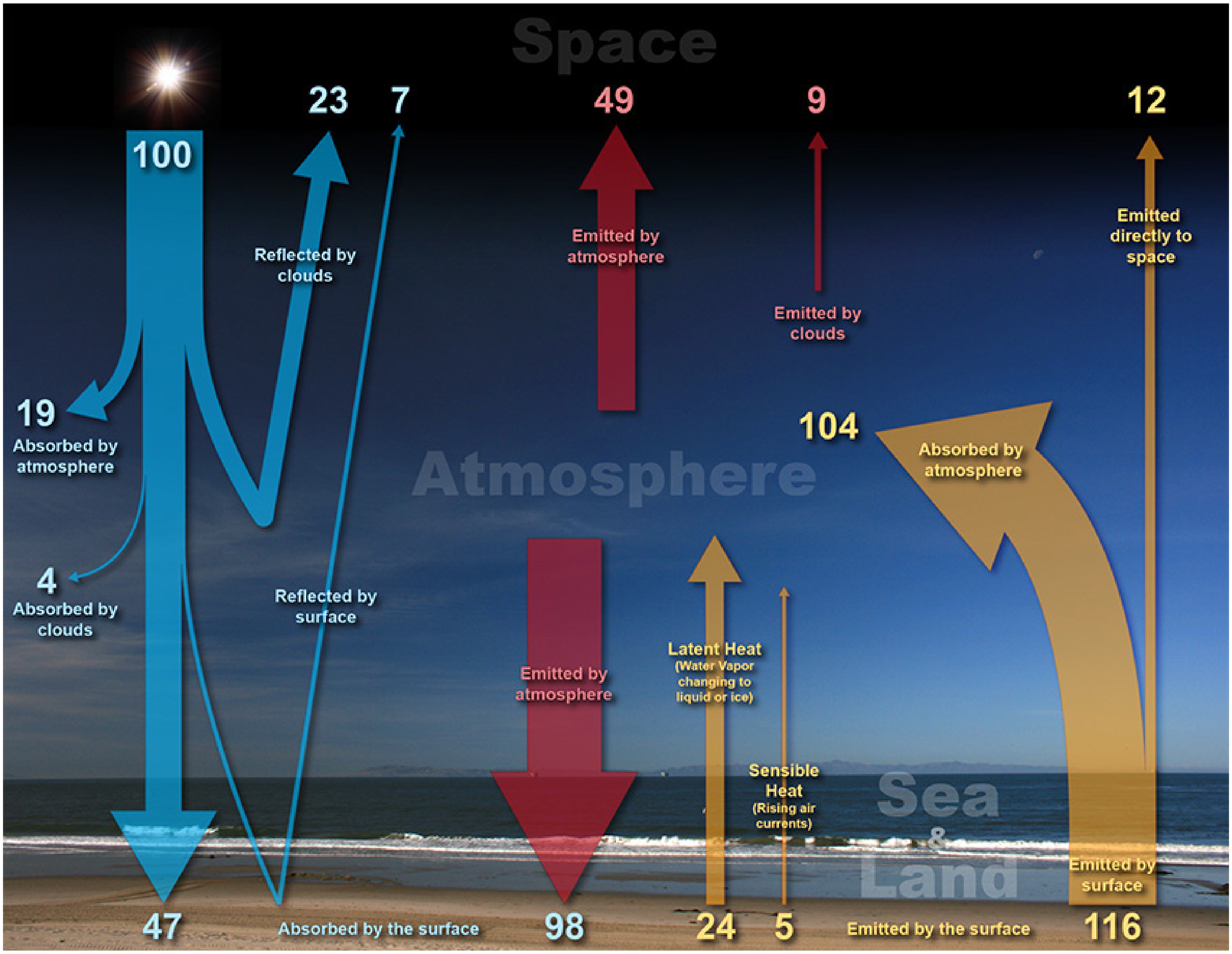

Figure 1: How the sun's energy entering Earth's atmosphere affects climate change, using 100 units of the sun's energy as a baseline. When the amount of energy entering the Earth's system is greater than the amount leaving, the Earth's system warms. This energy imbalance drives climate change.[5]

Energy flux at the Earth's surface: Approximately 47 of the 100 units of incoming shortwave energy from the sun are absorbed by the Earth's surface and emitted as longwave radiation that is invisible to the human eye. The vast majority of this longwave radiation, 116 units of energy, is emitted into the atmosphere. An additional 29 units of energy leave the surface of the Earth in the form of rising hot air (5 units of energy) and latent heat (24 units of energy).[6] A modest amount of longwave radiation (12 units of energy) is emitted directly from the surface to the top of the atmosphere. The Earth emits more energy than it receives because a portion of the energy absorbed by the atmosphere (shortwave from the sun, longwave from the Earth) is re-emitted back to the Earth's surface.

Energy flux within the atmosphere: As noted above, the atmosphere absorbs shortwave radiation directly from the sun (23 units of energy illustrated by the leftmost blue arrows in Figure 1 above), directly from the Earth's surface (104 units of energy), and from rising hot air and latent heat (29 units of energy). Approximately 98 units of energy are re-emitted as heat towards the Earth's surface, while 58 units of energy are re-emitted to the top of the atmosphere. The more greenhouse gases accumulate in the atmosphere, the more longwave radiation is "trapped" and warms the Earth's surface.

In the absence of natural radiative forcings and feedbacks (e.g., volcanic eruptions) and anthropogenic radiative forcings and feedbacks (e.g., GHG emissions from vehicles or power plants), the annual total radiative energy leaving the Earth would equal the amount of the sun's energy arriving on the Earth.[7] A destabilization of this balance causes global warming, in which the amount of radiation leaving the Earth is currently less than the amount of the sun's energy arriving. This deficit, or equivalently the excess energy that remains, is called the Earth's radiative imbalance, measured in flux units of W/m^2.

The Earth's system adjusts to this excess energy by warming until the amount of departing energy equals the amount arriving, totaling millions of megawatts.[8] The IPCC's 6th Assessment Report estimates that the Earth's energy imbalance was 0.50 (ranging from 0.32 to 0.69) W/m^2 for the period 1971–2006, and increased to 0.79 (ranging from 0.52 to 1.06] W/m^2 for the period 2006–2018, expressed per unit area of Earth's surface.[9] Figure 2 illustrates the monthly changes in the Earth's energy imbalance over the last approximately 40 years. As of April 2024, the Earth's energy imbalance was 1.04 W/m^2.

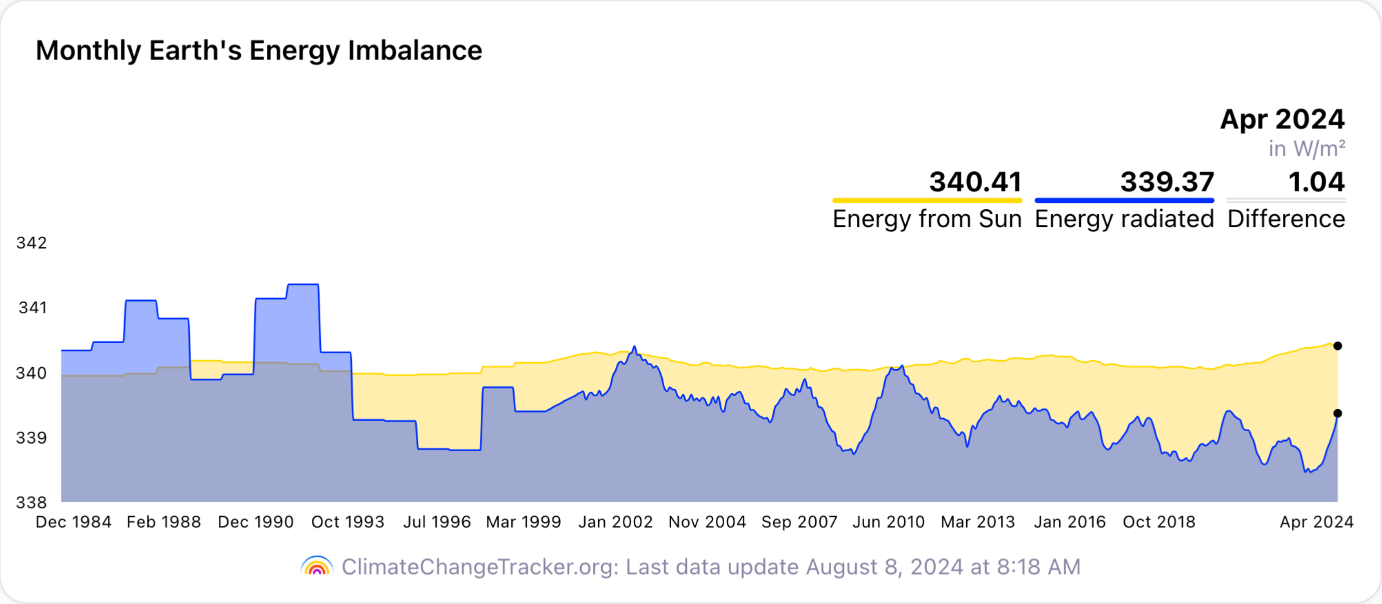

Figure 2: Earth's energy imbalance reported on a monthly basis between December 1984 and April 2024. As of April 2024, the Earth's energy imbalance is 1.04 W/m^2. Source: climatechangetracker.org accessed August 2024.

The Earth's albedo is an important driver of radiative forcing. Raising the Earth's albedo increases the percentage of sunlight that is reflected by the surface and reduces the amount of sunlight that is absorbed and re-emitted as thermal infrared radiation. The Earth's albedo is declining. Higher temperatures reduce the area covered by high-albedo surfaces such as sea ice, glaciers, and snow, and increase the area covered by low-albedo water. Further, global urbanization and urban development result in the replacement of natural areas with darker, impermeable built environments. Figure 3 illustrates the average albedo of surfaces commonly found on Earth.

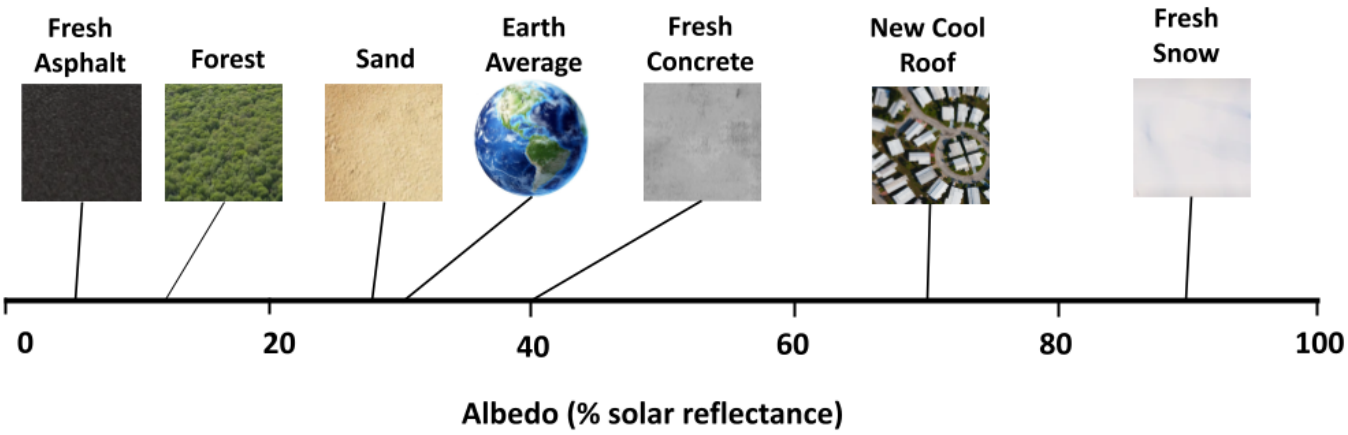

Figure 3: The albedo of common surfaces: Fresh asphalt reflects approximately 5% of the sun's energy. Forest reflects 10% to 15%. Sand reflects 30%. Earth's average albedo is 30%. Fresh concrete reflects between 25% and 50%. New cool roofs reflect between 25% for steep slope shingle roofs to over 90% (i.e., for a roof freshly coated with a very white coating product). Clouds reflect 75% to 85%. Fresh snow reflects 90%.[10,11]

Is albedo management of the built environment (AMBE) the same as solar geoengineering?

No. Solar geoengineering tends to include large-scale atmospheric- or space-based interventions such as stratospheric aerosol injection (SAI) and marine cloud brightening (MCB), as well as nascent ideas for both cirrus cloud thinning (CCT) and space-based technologies.[12] It may also include ideas to modify the albedo of large surface areas such as water bodies or agricultural areas. By contrast, AMBE primarily involves small-scale changes to our built environments, including roads, parking lots, rooftops, and walls, which total <1% of the Earth's surface.[13] A focus on the albedo of the built environment both reduces the global energy imbalance and provides a range of benefits to the places and people near the intervention, including reduced surface and air temperatures, improved thermal comfort and health outcomes, and reduced energy demand for cooling.

CONNECTING ALBEDO MANAGEMENT AND GHG MANAGEMENT

Because of its important role in radiative forcing, albedo management of the built environment (AMBE) can be a useful tool in the broader effort to mitigate climate change. Just as human interventions have reduced albedo on many parts of the land surface, human interventions can increase albedo through, for example, selecting different materials and practices in the design and construction of the built environment. To the extent that the impacts of AMBE can be measured, they can be compared with and integrated into other forms of climate mitigation policy, practice, and finance.

Research allows us to quantitatively compare the radiative forcing of different GHGs using global warming potential (GWP), the radiative forcing of 1 kg of a GHG divided by the radiative forcing of 1 kg of CO_2. The radiative forcing of the compared GHG and CO_2 are each integrated over 100 years following emission.[14]

Because albedo change alters radiative forcing, one can compute the GWP of an albedo change analogously to the GWP of a GHG emission, with the caveat that the atmospheric cooling induced by increased albedo is primarily a local phenomenon while the warming effect of higher GHG concentrations is global. The global warming potential of albedo (GWP_A) is the radiative forcing due to 0.01 (1 percentage point) increase in albedo on 1 m^2 of the Earth's surface, divided by the radiative forcing resulting from 1 kg of CO_2 emitted into the atmosphere. A negative value of GWP_A means that an albedo increase offsets the warming effect of GHGs in the atmosphere.

Peer-reviewed values for GWP_A, expressed in CO_2 equivalence, range from -2.55 kg/m^2 to -7.50 kg/m^2 when integrated over a 100-year time horizon. Values for this equivalence have ranged widely depending on the analysis period, season, and other location-specific factors such as cloud cover, latitude, elevation, and typical particulate levels in the air. Appendix C includes more detail on the variables affecting GWP_A and the coefficients used to measure them. For example, one study estimates that between latitudes 45°S and 45°N, the global annual average GWP_A, expressed in terms of CO_2, is -7 kg/m^2 over a 300-year time horizon;[15] while another study estimates that for locations in the United States, the annual average GWP_A lies between -1.6 and -0.8 kg/m^2 over a 50-year analysis period.[16] Additional research is needed to address the lack of additivity of radiative forcing from land albedo change and greenhouse gases due to the spatially concentrated nature of albedo-induced climate disturbances. Coordination with policymakers and the finance community will be needed to make the equivalence between albedo and GHG management relevant for policymakers and the investment community.

GWP_A and Time

Understanding and accounting for the complex relationship between GWP_A and time will be a principal challenge of making albedo increases fungible with GHG reductions. Three domains of time-sensitivity are relevant to investment and policy: changes in project albedo, project duration, and decay of the CO_2 reference pulse.[17]

Changes in project albedo: Albedo projects will experience changes in their effectiveness as albedo changes over time due to surface degradation, soiling, and exposure to the elements. Figure 4 illustrates the reduction in albedo over time with a study of selected white roofing membranes exposed at an outdoor test facility at Oak Ridge National Laboratory in Tennessee. Assessing how albedo changes over time in various locations, use cases, and maintenance programs is crucial to support the design of public policy and market-based mechanisms that value GWP_A.

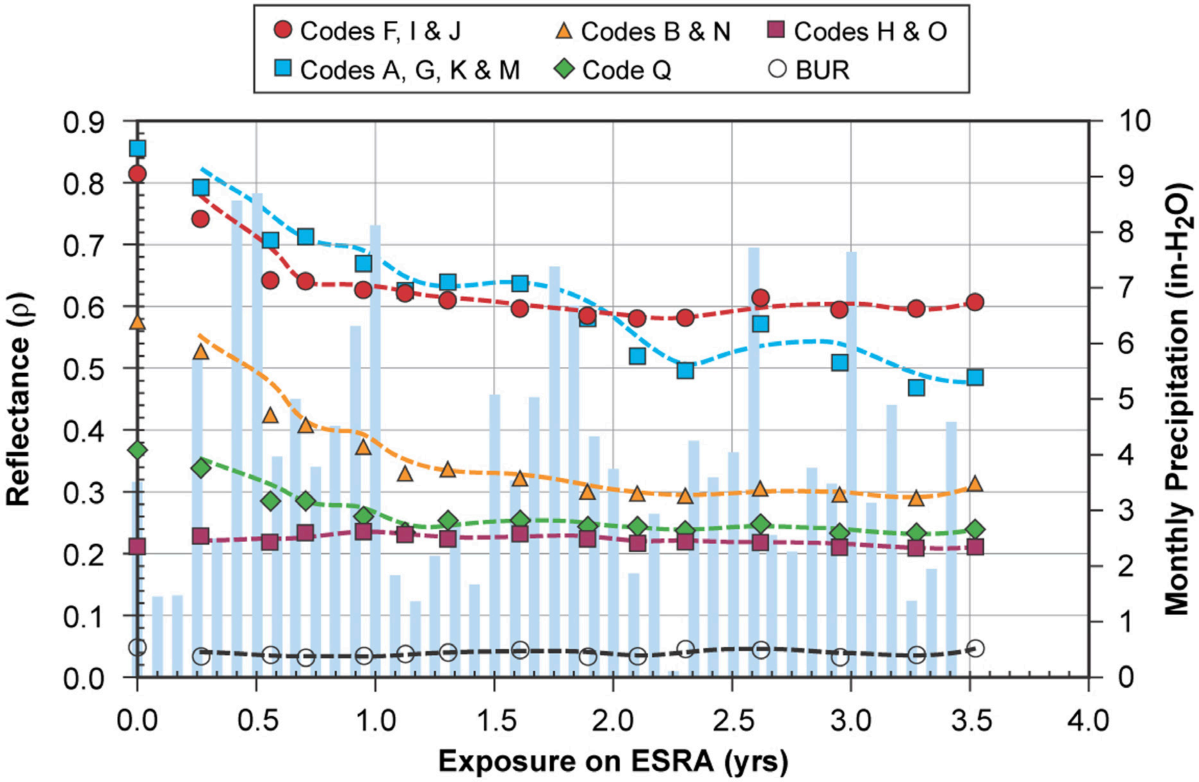

Figure 4: Evolution over 3.5 years of the solar reflectances of selected white roofing membranes exposed to the elements at Oak Ridge National Laboratory's Envelope Systems Research Apparatus (ESRA), an outdoor testing facility in east-central Tennessee. The light blue bars indicate monthly precipitation at the ESRA exposure site.[18]

Project duration: The efficacy of a project's albedo is also affected by the expected useful life of the surface itself. The timescales of an albedo-increasing project may differ from those of a project to mitigate GHG emissions. If albedo at a project site returns to its pre-project value, the benefits of the project's change to radiative forcing are lost. In contrast, if a renewable energy project avoids GHG emissions, the climate impact of the avoided emissions persists for the atmospheric lifetime of the avoided emissions.

The GWP_A metric is only accurate to the extent that the albedo project lasts as long as the time horizon used for the calculation of GWP_A. Shortening the time horizon to calculate GWP_A to something closer to the actual project life, calculating albedo change over time into project-specific GWP_A calculations, or changing policy to encourage longer-lived projects could address this potential mismatch in effective timescales.

Figure 5 illustrates the findings of a study modeled over 100 years comparing the radiative forcing effect of a cool pavement intervention with an expected life of 40 years to the effect of 1 kg of emitted CO_2. The cool pavement intervention (shown in orange) generates substantial negative radiative forcing effects compared to the emitted CO_2 (shown in purple), but generates those effects only during its 40-year lifespan. The periodic changes in the albedo-driven radiative forcing of the cool pavement over its life reflect maintenance and weather assumptions in the analysis.

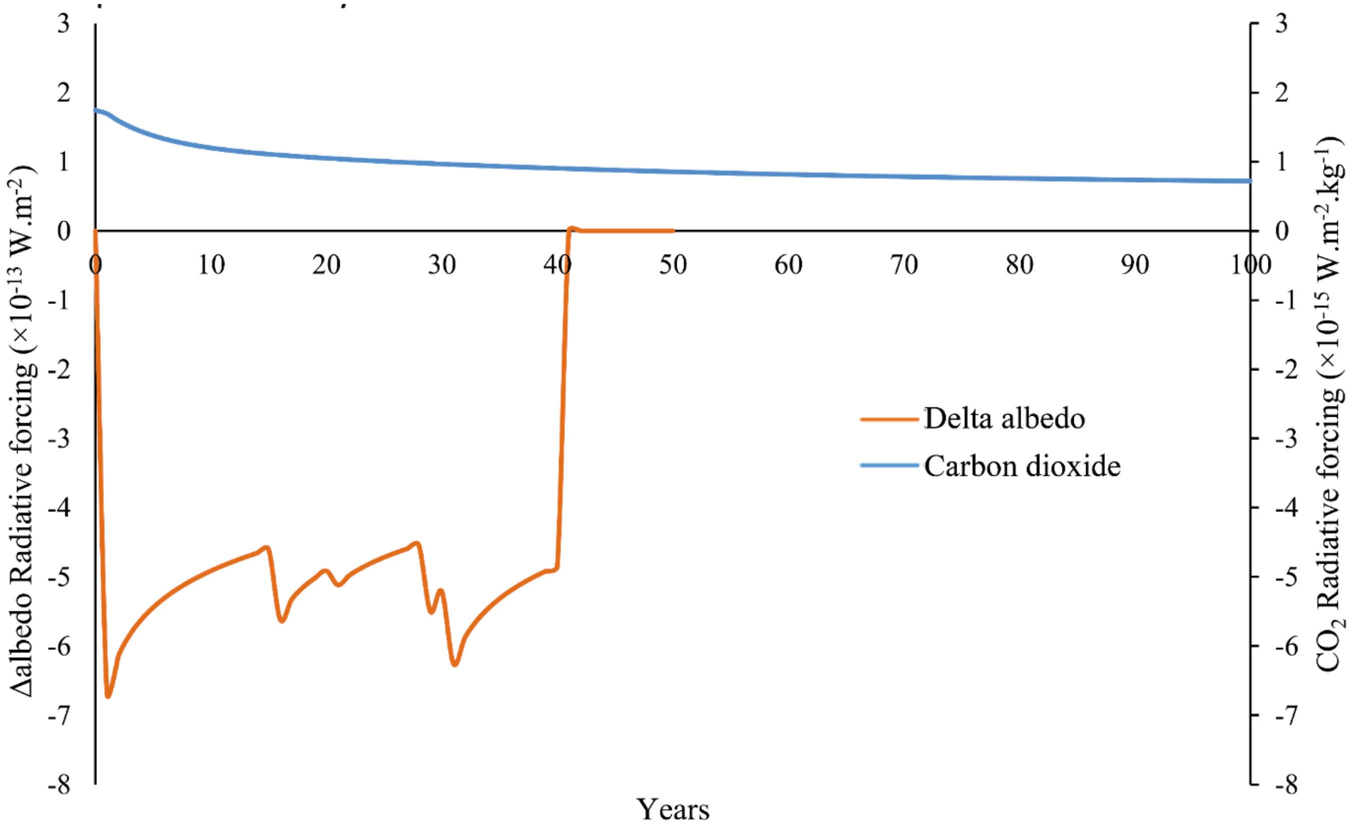

Figure 5 – Radiative forcing modeled over 50 years for a 40-year pavement project versus 1 kg of CO_2 over 100 years. The radiative forcing benefit from albedo change is greater than that of the CO_2 mitigation but occurs over a shorter time horizon.[19]

Decay of the CO_2 reference pulse: The reference radiative forcing of a 1 kg CO_2 pulse decays between emission and the time horizon and is not a constant value. This decay is illustrated in Figure 4 by the reduction of positive radiative forcing exhibited by the 1 kg CO_2 reference, shown in purple. Because the reference pulse changes over time, the computation of GWP_A should compare the radiative forcing of the albedo project and the CO_2 reference pulse over the time horizon of the analysis.

POTENTIAL SCALE OF THE EFFECT OF ALBEDO MODIFICATION

How much can managing albedo in the built environment rebalance the Earth's energy flux? Researchers have assessed aspects of this question, but policymakers have yet to vet a comprehensive model. As noted above, the current research gives a first-order approximation of significant potential climate benefits from surface albedo management at different geographic scales. Other studies looking at more detailed characteristics of specific interventions also point to the large potential size of benefits.

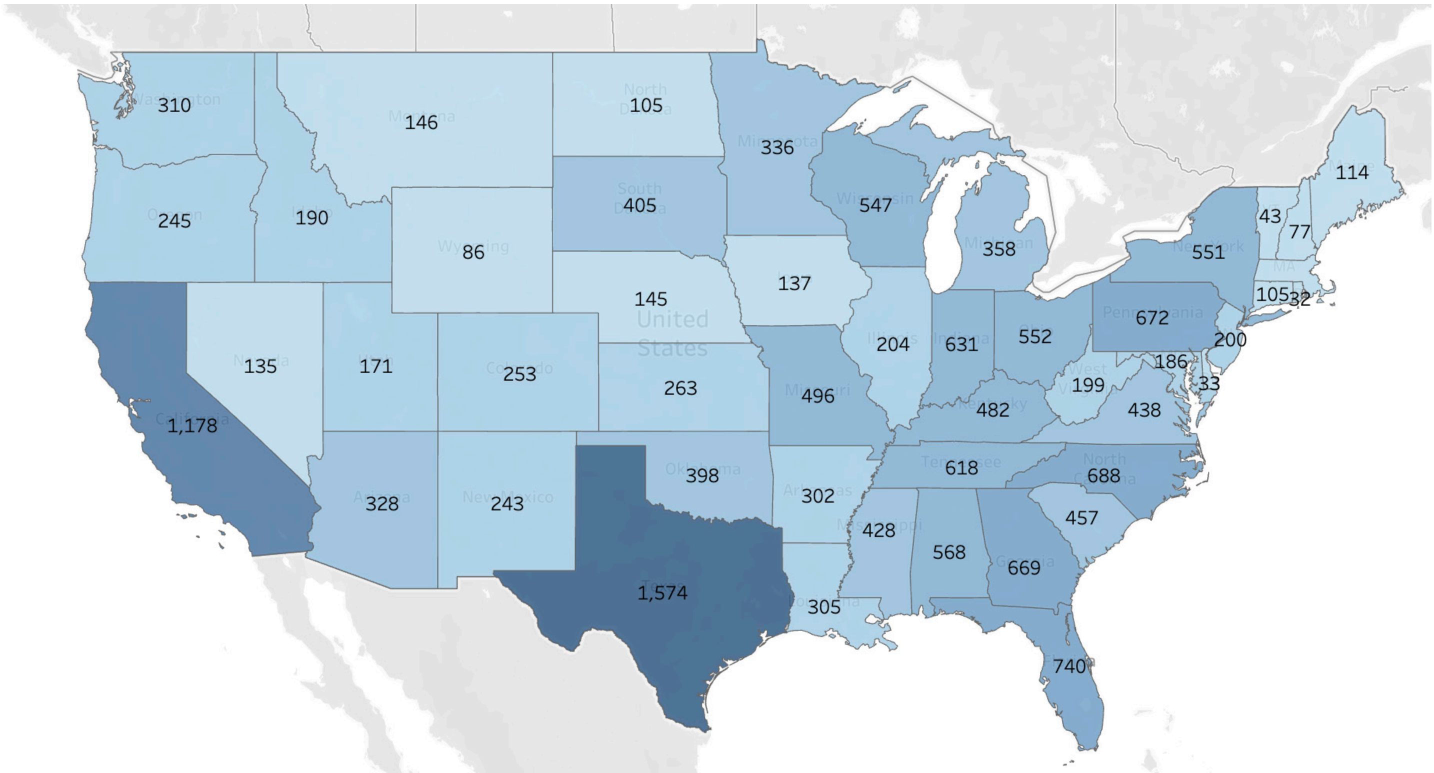

Figure 6 – Map of the state-level distribution of the 17 million metric tons of annual estimated GWP_A from a 0.20 (20 percentage point) albedo increase on urban and rural roads in the U.S.[20]

One study from MIT's Concrete Sustainability Hub assessed the change in CO_2e from radiative forcing due to a 0.20 albedo increase for all urban and rural asphalt roads in the United States.[21,22] While the authors acknowledge that GWP_A calculations could benefit from additional research and enhancements to existing climate models, their model estimates a total reduction of approximately 17 million metric tons of CO_2e (-17 Mt CO_2e) from a hypothetical single year of this albedo increase on roads across the United States.[23] In other words, the one-time effect on CO_2e reductions of decreasing radiative forcing by increasing the albedo of the road surface by 20 percentage points for one year would offset the warming effect equivalent to the annual GHG emissions produced by nearly 3.7 million personal vehicles – the equivalent of not driving more than 1 in 10 cars in California today for a year.[24,25] Figure 6 shows how this national reduction in CO_2e is distributed by state.

The authors also calculate GWP_A in cities, which experience an important local co-benefit from high-albedo surfaces. Cool pavements, walls, and roofs mitigate the UHI effect. They alleviate the need for residents and businesses to run air conditioning, particularly during extreme heat events, thereby further reducing urban GHG emissions from grid electricity. Even in cases where sunlight reflected by the cool pavement hits high-rise buildings, thereby increasing their energy demand for cooling, there is still a net climate benefit from deploying cool surfaces in urban areas through the combined benefits of radiative forcing and UHI mitigation.[26]

How are temperatures measured when determining the local effect of increasing surface albedo?

- There are several ways that temperature impacts can be measured to understand both the effect and possible tradeoffs of modifying the albedo of the built environment:
- Air temperature is the temperature of the air above the Earth's surface, adequately measured by a thermometer shielded from direct radiation and convection.
- Land surface temperature is the temperature of the Earth's surface as measured by aerial or satellite instruments, which usually differs from the air temperature near the ground.
- Wet bulb globe temperature (WBGT) is an environmental heat index that combines air temperature, humidity, wind speed, and radiant heat to estimate the heat stress on the human body.
- Heat index, or apparent temperature, is a simpler measure than WBGT that combines air temperature and relative humidity to estimate how hot it feels to the human body. Unlike WBGT, the heat index assumes the individual is in the shade and does not account for wind speed or direct sunlight.
- The Universal Thermal Climate Index (UTCI) is an index that integrates meteorological conditions like temperature, humidity, wind speed, and solar radiation into a single value to assess outdoor thermal comfort.
- Mean radiant temperature (MRT) is the average temperature of the surrounding surfaces that exchange radiation with the person.

The impact of higher albedo surfaces may differ across these temperature metrics. Depending on the use case, for example, it may be possible for a particular high albedo surface to generate substantial land surface cooling, slightly smaller air temperature reductions, and increased mean radiant temperatures. The temperature effect of higher albedo surfaces within a single metric (say, land surface temperature) will also differ based on the time of day.

ALBEDO MANAGEMENT TECHNOLOGIES

Humans have manipulated the Earth's surface albedo since we first began creating built environments. However, we often make these changes to our world without considering the consequences of altering solar reflectance or effect on the global climate. Today, dark roof, wall, and pavement materials cover much of our built environment. Figure 7 illustrates the difference in solar reflectance between built and natural environments in Las Vegas, where developed areas are noticeably darker and less solar reflective than the natural areas they border. Low-albedo surfaces absorb sunlight and increase temperature. However, across nearly every product category, there are higher-albedo options that reduce solar absorption, reduce heat gain, and could have a beneficial radiative forcing impact. Policies, regulations, and the market are increasingly focusing on these higher-albedo materials for roofs, walls, and paved areas.

Figure 7 – Satellite greyscale image of southeast Las Vegas and surrounding natural landscapes shows how roofing, wall, and pavement choices in urban environments have relatively low albedos, which influences the quantity of sunlight reflected back to space (Google Maps, retrieved February 19, 2023).

Efforts to alter the albedo of the built environment to balance the Earth's energy flux are a relatively new endeavor, dating back only over the last few decades. However, managing albedo for thermal comfort is a long-standing and widespread practice dating back hundreds, if not thousands of years. For example, light-colored surfaces and other design choices for indoor thermal comfort have been a common part of building practices in hot regions across the Mediterranean, northern Africa, and the Middle East and persist to this day. Some modern buildings are designed with high-albedo "cool roofs" and "cool walls" that reduce air conditioning demand, associated energy costs, and GHG emissions from grid electricity.

Figure 8 – A volunteer from Pacoima Beautiful applies a GAF cool coating to asphalt in the Pacoima neighborhood of Los Angeles. Source: Pacoima Beautiful.

Cool roofs, walls, and paved surfaces come in many different forms and colors.[27] An architect, engineer, or project owner can specify installing high-albedo building materials or applying a surface coating atop existing material, which can be as straightforward as a new coat of paint. Local public agencies can choose among concrete, asphalt coatings, reflective aggregates, and reflective binders (slag) for cool pavement projects. Figure 8 illustrates one option for cool pavement applied in the Pacoima neighborhood of Los Angeles.

It is important to understand that there is no one-size-fits-all solution among AMBE technologies. There is a wide variety of products included under the umbrella terms “cool roof,” “cool pavement,” or “cool surface.” These materials differ in how they provide cooling, the bands of the sun’s energy spectrum they reflect, the type of temperature reduction they generate, the trade-offs they embody, and the use cases and conditions for which they are appropriate. To achieve optimal outcomes and minimize unintended consequences, implementers must carefully consider these implications when choosing specific albedo management technologies.

What detrimental effects on health or the environment could be caused by new high-albedo technologies?

Most cool surface products are composed of materials already used daily. As with any technology, it is important to consider the appropriate use cases for high-albedo materials. For example, cooler urban air temperatures resulting from AMBE implementation at scale can reduce the formation of ozone but may slow wind flow that helps clear urban air pollution. Additional research may be needed for some high-albedo products to understand lifecycle GHG effects. Policymakers should assess AMBE interventions compared to the consequences and risks from plausible climate scenarios without AMBE in a risk-vs.-risk analysis.

POLICY PATHWAYS

Overview: A Need for Albedo Policy Development

U.S. markets for high-albedo products for roofs and walls are mature yet still growing, and there has been increasing interest and innovation in higher-albedo pavement products, which are newer to the market. The research community's continuous efforts to assess these products' abilities to mitigate UHI, reflect sunlight, endure local conditions, improve health outcomes, and satisfy other performance criteria support this growth. However, policies and regulations to manage the albedo in the built environment are nascent and not yet widespread.[28]

In the U.S., climate resilience and sustainability strategies are increasingly highlighting the benefits of implementing AMBE, including in the White House's July 2024 Climate Resilience Game Changers Assessment.[29] However, policy development and enforcement for many AMBE interventions remains nascent. Few policies and programs govern the albedo of pavements, and only Hawaii and California have building code provisions for exterior walls. Since 1999, several widely used building energy efficiency standards, including ASHRAE 90.1, ASHRAE 90.2, the International Energy Conservation Code and California's Title 24 have adopted cool-roof credits or requirements.[30] Chicago, California, Florida, and the IECC added cool roof requirements to their building codes over the next four years.[31] Moreover, most regulations based on the International Energy Conservation Code and ASHRAE Standard 90.1 apply only to specific climate zones and are often limited to low-sloped roofs on commercial and large multifamily buildings.[32] Much opportunity exists to expand albedo policies to apply in all climate zones, for all building types, and to cover a wider swath of the built environment, including paved areas.

Policy-based Mechanisms

Coordinated support for AMBE among local, state, and federal policymakers could accelerate the widespread deployment of high-albedo surfaces. Policy coordination could also provide guidelines to ensure these projects maximize local and global climate benefits. Additionally, to produce the greatest impact, policies and programs must focus on existing buildings and roads and not be limited only to new construction. Six approaches stand out as potential policy pathways for advancing AMBE.

1. **Research.** Albedo's fundamental role in the climate system is well-understood and documented in scientific literature, but many research gaps remain.[33] There is a need for targeted investments at the Department of Energy, Department of Housing and Urban Development, Department of Commerce (which includes the National Oceanographic and Atmospheric Administration), Environmental Protection Agency, Department of Transportation, and the National Science Foundation to support the further development of research that advances:
    - more comprehensive climate and benefit models;
    - better detection of albedo and longwave radiation emissions using satellite, aerial, and ground sensing;
    - greater understanding of cool pavement options; and
    - benefit/cost calculations that facilitate including albedo projects into climate finance regimes such as the economic effects of better public health, improved worker productivity, and savings on public works projects.

The federal government should support public-private partnerships to develop, evaluate, and commercialize high-albedo products for pavements, roofs, and walls in urban and rural environments. It should also expand support for materials science research that advances the development of high-albedo materials that optimize durability, longevity of high-albedo characteristics, UHI mitigation, and climate benefits under various conditions in the built environment. Additionally, satellite data to better account for time-, location-, and physics-dependent factors could strengthen existing models that evaluate the impact of surface albedo projects.[34]

The United States Global Climate Change Research Program (USGCRP) should play a key role in a coordinated interagency research effort. Established by the Global Change Research Act of 1990, USGCRP's mission is to produce "information readily usable by policymakers attempting to formulate effective strategies for preventing, mitigating, and adapting to the effects of global change."[35] USGCRP's research mission focuses on Earth system processes. USGCRP also convenes agencies to coordinate the development of new approaches, such as downscaling climate information to enhance its local relevance and co-producing knowledge at the regional scale.[36]

USGCRP comprises 14 federal agencies that conduct or apply research on climate change and is steered by the Subcommittee on Global Change Research (SGCR) of the National Science and Technology Council's (NSTC) Committee on Environment, which is overseen by the White House Office of Science and Technology Policy (OSTP).[37] USGCRP would facilitate engagement with other interagency bodies such as the National Climate Task Force (NCTF), the Interagency Working Group on Environmental Justice (EJ IWG), the National Integrated Heat Health Information System (NIHISS), and the Interagency Sustainability Working Group (ISWG).[38] USGCRP would also support these AMBE research efforts with other subcommittees within the NSTC's Committee on Environment, such as the Subcommittee on Resilience Science and Technology (SRST) and the U.S. Group on Earth Observations (USGEO).[39] Moreover, USGCRP could facilitate surface albedo research modeling efforts with the NOAA Earth's Radiation Budget (ERB) program and the Geoengineering Model Intercomparison Project (GEOMIP) at Rutgers University.[40]

2. **Codes and standards.** Building energy codes can regulate the albedo of roofs and walls by establishing minimum solar reflectance values. Typically, building energy codes in the U.S. stipulate a minimum "aged" value that takes into account the degradation in albedo resulting from 3 years of outdoor exposure and thus indicates the long-term albedo expected for the material. State and local building codes and standards should mandate cost-effective surface characteristics that increase AMBE that provide flexibility to property and asset owners in how they achieve them.

   Officials should tailor those mandates for retrofitting existing buildings and pavements within local climate zones. Local jurisdictions, most notably in California, have started to adopt cool-roof policy mandates for both new construction and existing buildings that need re-roofing or significant roof repairs. In most states, local governments may enact more stringent requirements than state-level building codes, making municipalities early adopters and experimental testbeds of surface albedo policy. For city-maintained pavements, local codes can be similarly deployed to regulate the minimum surface reflectance (and, for safety reasons, the maximum visible light reflectance) of roads and other paved surfaces.

   At the federal level, USGCRP could coordinate relevant agencies to support states and local jurisdictions regarding the development of surface albedo codes and standards for the built environment. For example, the National Institute of Standards and Technology (NIST) works with NOAA and other Federal and non-Federal parties to identify a consistent and authoritative set of forward-looking climate data and projections for the standard-setting process. USGCRP could work with the National Climate Services Partnership (NCSP) to use the convening power of the Federal government to share best practices for codes and standards among Federal and other government entities. These programs could also coordinate Federal engagement with nonprofit organizations that advise on and advocate for codes and standards.[41] This engagement could also include voluntary green building certification programs such as U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) program.

3. **Government construction standards for facilities and infrastructure.** Governments can be early adopters that drive markets for high-albedo construction materials and surface coatings on publicly owned assets. Officials can apply government construction standards at any level: federal, state, tribal, or local. In addition, the public sector can require new and existing public buildings, parking lots, and other structures to meet minimum reflectance requirements. Requirements may transform building stock most readily because many roof types have a lifespan of about 20 years and may undergo more frequent repair and maintenance.[42] Similar opportunities exist to increase the solar reflectance of exterior walls when they are routinely repainted. Requirements may also offer fairly rapid market transformation opportunities for asphalt pavements, which, depending on their type, use case, and the maintenance program in place, may be resurfaced every 7-10 years.[43] Concrete pavements may last 30 to 50 years between replacements.[44]

   Government agencies can also incorporate surface albedo standards into existing policies, such as the U.S. General Services Administration's (GSA) Facilities Standards for the Public Building Service (P100) for public facilities and infrastructure projects.[45] USGCRP could coordinate an interagency effort with relevant federal agencies. For example, NIST works on other climate-related building standards through the National Windstorm Impact Reduction Program (NWIRP) and through its mandate by the National Construction Safety Team (NCST) Act, which authorizes NIST to investigate extreme weather events on buildings and inform the improvement of codes for the built environment.[46] The U.S. Department of Housing and Urban Development (HUD) establishes construction and safety standards and promotes the use of cool roofs as a climate resilience strategy eligible for HUD funding.[47] A similar approach could be applied to pavements by the Federal Highway Administration (FHWA). The Department of Energy (DOE) proposes energy efficiency standards for manufactured homes, which account for approximately 10% of single-family houses constructed in the U.S. annually and could incorporate cool roofs and cool walls.[48] Action within these organizations would accelerate implementation, create product demand that could ultimately lower product costs, spur more product innovation, and signal acceptance and endorsement of these interventions.

4. **Albedo-based offsets or credits.**[49] GHG emissions allowance programs, such as cap-and-trade systems and voluntary carbon markets, set a limit on the total amount of GHG emissions that can be released (by a specific industry, entity or the entire economy), and typically that limit declines over time. Programs then allocate allowances to entities that permit them to emit a certain amount of emissions and/or trade allowances to find the most cost-effective ways to reduce emissions. These emissions allowances can be retired, which removes them from circulation after they have been used to account for an entity's emissions, ensuring that the carbon benefit they represent is not double-counted and preventing the same allowances from being used again in the future.

   Because GWP_A can be computed, a GHG regulatory system can allow projects that increase surface albedo to offset the solar forcing impact of GHG emissions and generate carbon credits.

   It is often the case that no carbon credits are available that originate from the same community where GHG emitters are located. Incorporating albedo-based offsets or credits would likely increase the number of surface albedo-increasing projects close to those emitters, thus reducing the geographical distance between the climate harm and the co-benefits generated by the project. Carbon schemes could prioritize surface albedo offsets or credits generated within its jurisdiction to advance climate equity objectives. Alternatively, carbon schemes could incentivize surface albedo projects to locate where they would deliver the greatest solar-forcing benefits.

   Most regulations to cap GHG emissions or schemes include a mechanism that allows some GHG reduction projects from outside the regulatory jurisdiction to substitute for allowing a small fraction of emissions allowance retirements. This mechanism could be expanded to include surface albedo-increasing projects. These carve-outs can be written to address existing buildings and roads, where most AMBE potential resides. USGCRP could work with other interagency bodies such as the National Climate Task Force, the Federal Interagency Working Group on Environmental Justice, and the Interagency Sustainability Working Group to pursue a research agenda that supports the development of carve-outs for albedo management projects.

5. **Stipulations on government funding.** Though the U.S. government does not regulate GHGs directly, it frequently exerts influence through stipulations on federal funding. Using this mechanism to enforce minimum surface albedo standards could kick-start greater recognition of the climate benefits of AMBE. For example, states depend on the federal government for highway funding, and such support could include stipulations regarding the solar reflectance of pavement materials. Though it is less common for state or local governments to utilize this mechanism, any government that disburses funding could apply such requirements. For example, this approach could apply to the maintenance and renovation of existing buildings and infrastructure, which would be helpful in achieving large-scale AMBE. USGCRP could coordinate information sharing with NIST, NCTF, and DOE's United States Cool Surfaces Deployment Project to attach best practices for AMBE with government infrastructure funding, particularly to provide local community cooling benefits to residents of disadvantaged communities, in alignment with the Justice40 initiative.[50]

   This mechanism can be effectively coupled with recommendations in 3: *Government Construction Standards for Facilities and Infrastructure*, above.

6. **Large-scale pilot projects.** Pilot projects can provide a platform for testing new performance standards and technologies. They present excellent opportunities for local, state, and federal policymakers to pursue AMBE for both new and existing buildings and roads. They can also generate case studies to increase public awareness of AMBE and its role in combating climate change.

   For example, the City of Los Angeles's Bureau of Street Services and its project partners recently implemented cool pavement across a 18-square block "cool community" research project in the Pacoima neighborhood of Los Angeles.[51] The project team compiled its key learnings from the project into a Cool Community Playbook and is sharing it publicly for other municipalities to learn from as they look to implement similar projects. Dr. Haider Taha of Altostratus published a peer-reviewed study in March 2024 that found cool pavement applications reduced temperatures on the surface and in the air near the surface.[52]

   Federal agencies are accustomed to supporting local governments or private companies through grants or technical assistance programs. US DOE supports the United States Cool Surfaces Deployment Project described above that includes efforts to develop major pilots of high-albedo surfaces. USGCRP could coordinate with other interagency bodies such as the NCTF, the EJIWG, and the ISWG, as well as the United States Cool Surfaces Deployment Project, to accelerate a cool surfaces research agenda that integrates large-scale cool surfaces pilot projects, in alignment with the environmental justice goals of the Justice40 initiative.[53]

   These projects may also provide a platform for developing voluntary offset markets for AMBE, as described in *Market-based Mechanisms* below.

Market-based Mechanisms

Although the federal government has launched programs to address methane emissions and issued CO_2 regulations for power plants, a comprehensive approach to GHG regulation has yet to form at the federal level. In its place, private markets have made nascent efforts to finance projects that avoid, reduce, capture, or sequester GHGs. Sustainable finance markets have developed bond and loan products to support these projects, and the Voluntary Carbon Market (VCM) has established GHG offset trading regimes to fund projects in exchange for GHG credits.

The >4 billion USD sustainable finance market includes green bonds/loans, social bonds/loans, sustainability bonds/loans, sustainability-linked bonds/loans, transition bonds/loans, and emerging instruments such as blue loans. Green bonds dominate the market: of the 990 Billion USD in sustainable finance issuances in 2023, approximately 60% were green bonds.[54] Under the Green Bonds Principles, AMBE projects in the built environment qualify for green bonds' use of proceeds, and therefore can be financed.[55]

Within the sustainable finance ecosystem, second-party opinion providers assess whether a bond issuance qualifies as a green bond; they tend to look to environmental regulations, standards, and certifications to confirm whether the use of proceeds qualifies under the Green Bond Principles. For example, cool roofs and cool walls qualify for the use of proceeds of green bonds for projects that earn points under the Urban Heat Island credit for the Leadership in Energy and Environmental Design (LEED) certification program.[56,57] Within California, compliance with CALGreen (the Green Building Standards Code, Part 11 of Title 24 of the Code of California Regulations, also known as "Title 24") helps to qualify cool roofs for the green bonds' use of proceeds.[58] Globally, second-party opinion providers also look at alignment with other sustainability indicators, such as the United Nations Sustainable Development Goals and the project(s) owner's publicly announced net-zero targets.

While sustainable finance tends to build on the practices and markets of traditional financial institutions, the VCM depends on new methodologies and registries to establish science-based standards and transparency in measuring, regulating, and reviewing GHG credit projects.[59] These methodologies and registries serve to ensure that the projects are credible for individuals or companies to utilize those credits to offset their GHG emissions footprint.[60] Each VCM methodology defines the project type and specifies the algorithms and constants that assign a GHG reduction to that type of project. The market assigns a monetary value to each credit corresponding with one metric ton of CO_2 that a project reduces, avoids, or removes. The VCM is poised for significant growth, with the potential to reach 50 billion USD by 2050.[61]

As discussed in the *Connecting Albedo Management* and *GHG Management* section above, the GWP metric creates an albedo-GHG equivalency through radiative forcing, which may also provide the basis to develop a AMBE methodology for the VCM. The associated credit could correspond with a high-albedo project's benefit in terms of its GHG-equivalence (CO_2e).[62] In that way, the VCM could value and trade the credit.

The VCM's registries offer mechanisms by which external parties can propose a new methodology to cover a project type that the market has yet to recognize. Third-parties develop new science-based methodologies through a public, multi-stakeholder engagement and approval process, including a public comment period. This process would provide an avenue for introducing AMBE into a relatively mature framework of GHG management. Establishing a surface albedo-based GHG offset methodology approved by a reputable registry could attract more funding from private capital for AMBE projects, increase the sources of funding available, improve access to existing climate finance mechanisms, and accelerate the global installation of these projects for managing radiative forcing.[63]

However, to attract private capital, the VCM will require metrics, methods, and tools to estimate, measure, and verify the radiative forcing benefits associated with albedo projects.[64] As described in the *Who We Are* section below, Climate Resolve recently launched its *Shine On* initiative, including both a Finance Working Group and a Technical Working Group. The Finance Working Group is developing and implementing a roadmap to expand the use of market-based mechanisms to attract more capital to AMBE projects. The Technical Working Group is developing the necessary metrics, methods, and tools. *Shine On* will publish a separate report documenting these working groups' analyses and recommendations in 2025.

ABOUT THE AUTHORS

For more than a decade, our nonprofit organization Climate Resolve has worked with partners and other stakeholders to elevate peer-reviewed research on high-albedo surfaces, successfully advocate for surface albedo policy solutions, and implement cool roofs, cool walls, and cool pavement projects in California.[65] In June 2022, Climate Resolve hosted *Reflecting Sunlight: Albedo as a Means to Reduce the Greenhouse Effect*, a scientific panel and webinar with four leading researchers from NASA Jet Propulsion Laboratory, Concordia University, Massachusetts Institute of Technology, and Lawrence Berkeley National Lab.[66] Their presentations included peer-reviewed findings about how to quantify the climate cooling benefits of increasing the surface albedo in the built environment in terms of CO_2e.

In 2023, with generous funding from the ClimateWorks Foundation's Clean Cooling Collaborative and the Grantham Foundation, Climate Resolve launched the *Shine On* initiative to continue efforts to better understand and quantify the climate effects of AMBE in the built environment and to identify strategies to integrate those benefits into policy and finance mechanisms. Climate Resolve is structuring multi-stakeholder participation in the *Shine On* initiative through our convening of the *Sol Collaborative*, which includes over 100 participants from 70 organizations coordinating within five interconnected working groups:

- The White Paper Working Group manages the development, editing, and publication of this white paper, including future updates, to describe the state of the peer-reviewed, scientific research on how surface albedo affects the Earth's energy balance.
- The Policy and Communications Working Group advances policy, codes/standards, and public funding in support of AMBE projects through an equity lens.
- The Technical Working Group is developing a comprehensive, dynamic tool to estimate, measure, and verify the radiative forcing (W/m^2) and GHG-equivalent (CO_2e) impacts of cool surfaces in urban, suburban, and rural communities worldwide.
- The Finance Working Group is preparing and implementing a roadmap to attract more private-sector capital into AMBE projects, particularly to benefit under-resourced communities.
- The Albedo Projects Working group is developing and implementing AMBE projects in Los Angeles County that will provide both UHI mitigation benefits and global cooling benefits and is documenting those benefits through impact studies in partnership with local academic researchers, who publish the studies in peer-reviewed journals.

The *Sol Collaborative* includes participants from the private, public, and nonprofit sectors; tribal entities; community-based organizations; industry associations; academia; research laboratories; and other interested stakeholders. Climate Resolve encourages the involvement of many voices and perspectives to build consensus and elevate AMBE in the built environment as a tool for climate change adaptation and mitigation worldwide.

CONCLUSION

Global warming results from radiative forcing, which can be changed by influencing two mechanisms: GHG emissions and surface albedo. Because policy tools are only being developed for one – GHG emissions – we are missing opportunities to invest in cost-effective offsetting opportunities that also generate large individual and societal co-benefits.

Albedo Management of the Built Environment are complementary interventions that immediately reduce local surface temperatures and the global energy imbalance while aggressive mitigation actions to reduce and remove those emissions continue in parallel. Increasing the solar reflectance of roofs, walls, and pavements can contribute significantly to efforts to address climate change by reducing the Earth's energy imbalance. A well-established body of research spanning 25 years allows us to compare the impact of projects that increase solar reflectance with those that mitigate greenhouse gas emissions.

While additional research is needed to refine impact models that provide a more comprehensive understanding of the effects of changing surface reflectance over time, science shows that AMBE in built environments can reduce global warming and generate local cooling co-benefits. High-albedo products already exist and can be immediately deployed at scale with federal, state, and local policy support. The public and private sectors should explore policy- and market-based approaches to properly value and incentivize investments that increase solar reflectance in an equitable, economically viable, and context-sensitive manner.

Appendix A: Endnotes

1 “NASA Analysis Confirms 2023 as Warmest Year on Record - NASA,” accessed August 14, 2024, https://www.nasa.gov/news-release/nasa-analysis-confirms-2023-as-warmest-year-on-record/.

2 The body of research indicates that urbanization has a clear local and regional climate effect but an uncertain effect on global climate change.

3 A more detailed description of this complex interaction between the Sun and Earth is included in the body of the white paper.

4 “Copernicus: June 2024 Marks 12th Month of Global Temperature Reaching 1.5°C above Pre-Industrial | Copernicus,” accessed August 14, 2024, https://climate.copernicus.eu/copernicus-june-2024-marks-12th-month-global-temperature-reaching-15degc-above-pre-industrial.

5 “The Earth-Atmosphere Energy Balance | National Oceanic and Atmospheric Administration,” accessed August 14, 2024, https://www.noaa.gov/jetstream/atmosphere/energy.

6 Latent heat is the heat removed from the surface for evaporation and sublimation.

7 There is a small quantity of geothermal energy making this balance more complex – about 0.087 W/m2. Because the quantity of geothermal energy is small, and because it is not anthropogenically affected, it does not affect the heuristic description of the radiative energy budget being given here.

8 This rebalancing occurs over decades and centuries and is driven by increased heat emission from the Earth’s surface, increased ocean uptake of heat, atmospheric and surface albedo changes, water vapor and GHG feedbacks, natural climate oscillations, and changes in atmospheric aerosol levels. Andrew E. Dessler, Thorsten Mauritsen, and Bjorn Stevens, “The Influence of Internal Variability on Earth’s Energy Balance Framework and Implications for Estimating Climate Sensitivity,” Atmospheric Chemistry and Physics 18, no. 7 (April 17, 2018): 5147–55, https://doi.org/10.5194/acp-18-5147-2018.

9 “Synthesis Report — IPCC,” accessed August 14, 2024, https://www.ipcc.ch/ar6-syr/.

10 “Valuing Albedo | MyNASAData,” accessed August 14, 2024, https://mynasadata.larc.nasa.gov/mini-lessonactivity/valuing-albedo.

11 Stella Tsoka, Katerina Tsikaloudaki, and Theodoros Theodosiou, “Coupling a Building Energy Simulation Tool with a Microclimate Model to Assess the Impact of Cool Pavements on the Building’s Energy Performance Application in a Dense Residential Area,” Sustainability 11 (April 30, 2019): 2519, https://doi.org/10.3390/su11092519.

12 “Congressionally-Mandated Report on Solar Radiation Modification | OSTP,” The White House, June 30, 2023, https://www.whitehouse.gov/ostp/news-updates/2023/06/30/congressionally-mandated-report-on-solar-radiation-modification/.

13 M. Zhao et al., “A Global Dataset of Annual Urban Extents (1992–2020) from Harmonized Nighttime Lights,” Earth Syst. Sci. Data 14, no. 2 (February 8, 2022): 517–34, https://doi.org/10.5194/essd-14-517-2022.

14 Though IPCC defines GWP according to a 1 kg pulse of CO_2 emitted into the atmosphere, professionals in GHG measurement and management typically work in units of metric tons rather than kilograms. From the point of view of the global atmosphere these are both infinitesimal units and the physics in the atmosphere will be identical per mass unit.

15 Hashem Akbari, H. Damon Matthews, and Donny Seto, “The Long-Term Effect of Increasing the Albedo of Urban Areas,” Environmental Research Letters 7, no. 2 (April 2012): 024004, https://doi.org/10.1088/1748-9326/7/2/024004.

16 Xin Xu et al., “Quantifying Location-Specific Impacts of Pavement Albedo on Radiative Forcing Using an Analytical Approach,” Environmental Science & Technology 54, no. 4 (February 18, 2020): 2411–21, https://doi.org/10.1021/acs.est.9b04556.

17 Roel Hammerschlag, “Bringing Albedo to the GHG Market,” Carbon Management 13, no. 1 (January 2, 2022): 372–78, https://doi.org/10.1080/17583004.2022.2098176.

18 David L Roodvoets, William A Miller, and Andre O Desjarlais, “Long Term Reflective Performance of Roof Membranes,” n.d.

19 Hessam AzariJafari, Ammar Yahia, and Ben Amor, “Removing Shadows from Consequential LCA through a Time-Dependent Modeling Approach: Policy-Making in the Road Pavement Sector,” Environmental Science & Technology 53 (January 3, 2019), https://doi.org/10.1021/acs.est.8b02865.

20 “Annual GWP Impact of Pavement Albedo Change | Tableau Public,” accessed August 14, 2024, https://public.tableau.com/app/profile/randolph.kirchain/viz/RFresultsperstateandcounty/StateTotal.

21 Xu et al., “Quantifying Location-Specific Impacts of Pavement Albedo on Radiative Forcing Using an Analytical Approach.”

22 There are more than 6 million rural lane miles in the United States, more than twice the approximately 2.7 million of urban lane miles. Combined with other location-based factors such as solar zenith angle and local climate zone, the authors demonstrate that increasing the albedo on roads in rural counties throughout the United States, particularly in the southwest and southeast, could provide significant radiative forcing benefits.

23 This model to estimate GWPA for cool pavements accounts for location-specific factors, such as urban can transmittance, which includes both a sky view factor and a factor due to vehicles covering roads. To calculate the radiative forcing benefits of cool roofs, the GWPA for roofs could be recalculated separately based on a relevant set of location-specific factors.

24 Average vehicle emissions of 4.6 tons per year from “Greenhouse Gas Emissions from a Typical Passenger Vehicle | US EPA,” accessed August 14, 2024, https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle.

25 Total of 31.3 million registered vehicles in California per “U.S: Motor Vehicle Registrations by State | Statista,” accessed August 14, 2024, https://www.statista.com/statistics/196505/total-number-of-registered-motor-vehicles-in-the-us-by-state/.

26 Hessam AzariJafari et al., “Urban-Scale Evaluation of Cool Pavement Impacts on the Urban Heat Island Effect and Climate Change,” Environmental Science & Technology 55, no. 17 (September 7, 2021): 11501–10, https://doi.org/10.1021/acs.est.1c00664.

27 The Cool Roof Rating Council (CRRC) is the primary organization for labeling and reporting solar reflectance of roofing materials and maintains the most extensive catalog of available cool roof materials. The CRRC launched a parallel program in January 2022 for exterior wall materials. Both are accessible at https://coolroofs.org/ . For pavements, the Cool Roadways Partnership website contains survey results of cool pavement materials available as of 2020, accessible at https://smartsurfacescoalition.org/global-cool-cities-partnership

28 Alhazmi, M., Sailor, D., Levinson, R. (2023). “A review of challenges, barriers, and opportunities to large-scale deployment of cool surfaces.” Energy Policy Volume 180, September 2023, https://doi.org/10.1016/j.enpol.2023.113657

29 “https://www.Whitehouse.Gov/Wp-Content/Uploads/2024/07/Climate-Resilience-Game-Changers-Assessment.Pdf,” accessed August 14, 2024

30 Hashem Akbari and Ronnen Levinson, “Evolution of Cool-Roof Standards in the US,” Advances in Building Energy Research 2, no. 1 (January 2008): 1–32, https://doi.org/10.3763/aber.2008.0201.

31 The Cool Roof Rating Council maintains a comprehensive database of municipal, state, and model code requirements for cool roofs and walls. https://coolroofs.org/resources/codes-programs-standards-2#cool-roof-model-codes-and-standards

32 Two exceptions: The City and County of Los Angeles require steep-slope residential roofs to be at least 0.25.

33 See Appendix B for references to peer-reviewed literature.

34 While this paper primarily focuses on U.S. policy and research opportunities, important and relevant work to increase our understanding of the effects of AMBE and how it can be incorporated into policy and investment decision-making is advancing globally.

35 “Appendix A: Global Change Research Act of 1990 | Accomplishments of the U.S. Global Change Research Program | The National Academies Press,” accessed August 14, 2024, https://nap.nationalacademies.org/read/24670/chapter/9.

36 “Appendix A: Global Change Research Act of 1990 | Accomplishments of the U.S. Global Change Research Program | The National Academies Press.”

37 “U.S. Global Change Research Program | GlobalChange.Gov,” accessed August 14, 2024, https://www.globalchange.gov/.

38 “Ibid.”

39 “Ibid.”

40 “Congressionally-Mandated Report on Solar Radiation Modification | OSTP”; “U.S. Global Change Research Program | GlobalChange.Gov.”

41 “NSTC: A Federal Framework and Action Plan for Climate Services | OSTP | The White House,” accessed August 14, 2024, https://www.whitehouse.gov/ostp/news-updates/2023/03/22/nstc-a-federal-framework-and-action-plan-for-climate-services/.

42 The lifespans of roofing products varies widely from approximately 5 years for some coatings to over 50 years for certain tile products. A fuller accounting of typical lifespans by roofing product can be found in the Cool Roofs and Pavements Toolkit. https://coolrooftoolkit.

org/wp-content/pdfs/CoolRoofToolkit_Full.pdf

43 Yichang (James) Tsai et al., “How Long Will Asphalt Pavement Last?,” 2010, https://trid.trb.org/View/919030.

44 James (Yichang) Tsai et al., “Georgia Concrete Pavement Performance and Longevity.,” February 1, 2012, https://rosap.ntl.bts.gov/view/dot/24739.

45 “Facilities Standards (P100) Overview | GSA,” accessed August 14, 2024, https://www.gsa.gov/real-estate/design-and-construction/engineering/facilities-standards-for-the-public-buildings-service.

46 “NSTC: A Federal Framework and Action Plan for Climate Services | OSTP | The White House.”

47 “2023 Manufactured Housing Facts: Industry Overview – MHI,” accessed August 14, 2024, https://www.manufacturedhousing.org/resource/2023-manufactured-housing-facts-industry-overview/.

48 Manufactured Housing Institute, 2023 Manufactured Housing Facts: Industry Overview, June 2023. https://www.manufacturedhousing.org/wp-content/uploads/2023/06/Industry-Overview.pdf

49 Carbon offsets are voluntary actions to compensate for emissions by funding projects that reduce or remove emissions, while carbon credits are tradable permits that allow a certain amount of emissions under a regulatory cap-and-trade system. Offsets are quantified based on the amount of emissions they mitigate and are driven by environmental responsibility, whereas credits are integral to government policies and provide economic incentives for emissions reduction through trading.

50 Ronnen Levinson et al., “United States Cool Surfaces Deployment Plan,” June 1, 2023, https://doi.org/10.2172/1988535.

51 “COOL SURFACES IN PACOIMA - Climate Resolve,” accessed August 14, 2024, https://www.climateresolve.org/cool-surfaces-in-pacoima/.

52 Haider Taha, “Micrometeorological Effects and Thermal-Environmental Benefits of Cool Pavements: Findings from a Detailed Observational Field Study in Pacoima, California,” Environmental Research Communications 6 (March 13, 2024), https://doi.org/10.1088/2515-7620/ad2a8e.

53 “Justice40 Initiative | Environmental Justice | The White House,” accessed August 14, 2024, https://www.whitehouse.gov/environmentaljustice/justice40/.

54 “Home - Environmental Finance Data,” accessed August 14, 2024, https://efdata.org/.

55 “Green Bond Principles » ICMA,” accessed August 14, 2024, https://www.icmagroup.org/sustainable-finance/the-principles-guidelines-and-handbooks/green-bond-principles-gbp/.

56 “Heat Island Reduction | U.S. Green Building Council,” accessed August 14, 2024, https://www.usgbc.org/credits/new-construction-core-and-shell-schools-new-construction-retail-new-construction-hospitali-1.

57 “Heat Island Mitigation with Cool Walls | U.S. Green Building Council,” accessed August 14, 2024, https://www.usgbc.org/credits/SSpc154-v4.1?return=/credits/New%20Construction/v4.1.

58 “CALGreen,” accessed August 14, 2024, https://www.dgs.ca.gov/BSC/CALGreen.

59 Well-known VCM registries include Verra, The Gold Standard, the Climate Action Reserve (CAR), and the American Carbon Registry (ACR).

60 Based on findings presented by Investopedia (https://www.investopedia.com/best-carbon-offset-programs-5114611) and CarbonCredits.com (https://carboncredits.com/the-4-best-carbon-offset-programs-for-2023/)

61 “https://www3.Weforum.Org/Docs/WEF_Scaling_Voluntary_Carbon_Markets_2023.Pdf,” accessed August 14, 2024, https://www3.weforum.org/docs/WEF_Scaling_Voluntary_Carbon_Markets_2023.pdf.

62 Alternatively, the credit could directly quantify the radiative forcing benefits in terms of the energy reflected to space (W/m2 or total MW), as a new form of “cooling credit.” However, establishing the viability of a cooling credit may require the development of a separate market of tradable credits, which may be a considerable challenge.

63 As an example of an existing climate financing mechanism, the Green Climate Fund (GCF) has issued 15 billion USD in financing for climate projects in 130 countries. An approved methodology for AMBE would help accelerate their inclusion in GCF projects to improve climate resilience that would generate both local and global benefits.

64 These metrics, methods, and tools also apply to green finance and cooling credits.

65 "COOL SURFACES IN PACOIMA," Climate Resolve (blog), accessed August 14, 2024, https://www.climateresolve.org/cool-surfaces-in-pacoima/.

66 "Reflecting Sunlight: Albedo as a Means to Reduce the Greenhouse Effect," Climate Resolve (blog), accessed August 14, 2024, https://www.climateresolve.org/reflecting-sunlight-albedo-as-a-means-to-reduce-the-greenhouse-effect/.

Appendix B: References and Related Literature

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Appendix C: Variables Determining Global Warming Potential of Albedo

Variable Type	Variable	Metric for Measurement
Physics-dependent variables	Surface reflectance	Solar reflectance (SR)
	Radiative forcing	Watts/square meter (W/m^2)
	Atmospheric composition	Aerosol extinction ($\alpha(\lambda)$)
Time-dependent variables	Duration of project albedo change	Months or years
	Time horizon of the study period	Years
	Degradation of the CO_2 reference pulse	Years
Location-dependent variables	Latitude	Degrees of latitude
	Land cover type	National land cover database
	Urban versus rural	National land cover database

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