TECHNICAL ASSESSMENT FOR ENERGY EFFICIENT ROOFS

SECTOR: BUILDINGS

AGENCY LEVEL: BUILDING OWNERS

KEYWORDS: GREEN ROOFS, COOL ROOFS, WHITE ROOFS, BUILDING EFFICIENCY, ENERGY EFFICIENCY, ROOF GARDENS, ROOF PARKS, HEAT ISLAND EFFECT

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*Note: For some of the technical reports, the result section is not yet updated. Kindly refer to the model for the latest results.

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info@drawdown.org www.drawdown.org

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ACRONYMS AND SYMBOLS USED

ASHRAE – American Society of Heating Refrigeration Air Conditioning Engineers

CRRC – Cool Roof Rating Council

CZ – Climate zone

ECRC – European Cool Roof Rating Council

EFB – European Federation of Green Roofs and Walls

EIA – Energy Information Administration

EPA – Environmental Protection Agency

FLL – German Landscape Research, Development & Construction Society

GBPN – Global Buildings Performance Network

GHG – Greenhouse gas

IEA – International Energy Agency

LBNL – Lawrence Berkeley National Laboratory

LEED – Leadership in Energy and Environmental Design

NRDC – Natural Resources Defense Council

NPV – Net Present Value

NZB – Net Zero Building

PDS – Project Drawdown Scenario

PM – Particulate Matter

PV – Photovoltaic

REF – Reference (Scenario)

RRS – Reduction and Replacement Solutions (Model of Project Drawdown)

SRI – Solar Reflectance Index

TAM – Total Addressable Market

TSR – Total Solar Reflectance

UHI – Urban Heat Island

USGBC – US Green Buildings Council

EXECUTIVE SUMMARY

Cool Roofs offer a zero- to low-cost, technically-proven path for reducing building space cooling loads and corresponding GHG emissions in warmer Climate Zones (CZs). Due to the "space heating penalty", cool roofs are not suited for most buildings in very cold climates. If widely adopted where applicable, Cool Roofs could reduce space cooling loads by approximately 9%. The result, in the Project Drawdown Optimum Scenario, would be installation of 142 billion m^2 of Cool Roofs by 2050, resulting in a reduction of 4.0 Gt of 2020-2050 CO_2 emissions compared with the reference Scenario. This would reduce atmospheric GHG concentration by 0.35 PPM CO_2-equivalent in 2050. Lifetime operating cost savings would total $1.7T from 2020 to 2050, with a lifetime cash flow savings NPV of $322B.

The number one challenge for global Cool Roof adoption, especially in developing countries, is a small first cost increment which can be a major barrier in low-cost applications. The key factors that have propelled Cool Roof market adoption include demonstration of functional performance and real-world economic value in the specific building context, in this case, mainly the USA, development of products tailored to local needs, and establishment of building codes and product rating standards.

Green Roofs offer similar thermal impact to reduce building space cooling loads, and also provide insulation that can reduce space heating. Though they have a higher first cost than conventional roofs, Green Roofs offer additional benefits, notably stormwater retention and mitigation, and the aesthetic of urban gardens. As living vegetated systems, Green Roofs with minimal irrigation are well-suited for middle CZs and for the non-arid portions of warmer CZs. If widely adopted where they are applicable, Green Roofs could reduce space cooling loads by approximately 10% and heating loads by 7%. The result, in the Project Drawdown Optimum Scenario, is installation of 45 billion m^2 of Green Roofs by 2050, resulting in a reduction of 1.3 Gt of 2020-2050 CO_2 emissions compared with the reference Scenario. This would reduce atmospheric GHG concentration by 0.1 PPM CO_2-equivalent in 2050, but *increase* lifetime operating cost by $1.2T from 2020 to 2050 and lifetime cash flow NPV by $2.6T.

Key barriers for Green Roofs include unsuitability of much of the existing building stock to bear the additional weight, high installation and maintenance costs, lack of supportive government policies and incentives, and lack of customer awareness and appreciation of the non-energy benefits of Green Roofs.

Given Green Roofs' first cost premium, government incentives that reduce Green Roof lifecycle cost are key to accelerating global adoption. Where Green Roofs have succeeded, notably in Germany and selected North American and Asian cities, success has been driven by government mandates / incentives for non-energy benefits, especially stormwater management, aesthetics, and biodiversity, and by development of the skill base and infrastructure needed to install and maintain Green Roofs.

1 LITERATURE REVIEW

Globally, the buildings sector is one of the largest end-use sectors, accounting for 30% of global final energy usage. Including building construction increases this to 36%. These two together account for 39% of energy-related CO_2 emissions (UN Environment & IEA, 2017). Thus, the global building sector needs innovative technologies and approaches to reduce energy consumption while ensuring building operations are not affected. Breaking down the building sector by energy end-use gives an idea of where the potentials lie. Space heating consumed 32% of final building energy in 2014. The other top uses are cooking energy (22%), water heating (19%), appliances and equipment (16%), and lighting (6%) (IEA, 2017). Clearly, there are many opportunities across the building sector for energy efficiency. Space and water heating energy is affected by windows, walls and heat source; cooking energy is affected by source and cooking technology; appliance energy by appliance efficiency and use; and lighting is affected by light technology and use.

1.1 STATE OF ENERGY EFFICIENT ROOFS

This Technical Assessment examines the space cooling energy reduction potential of two types of energy-efficient roofs: (US EPA Vocabulary Catalog)

- **"Cool Roofs"** use highly-reflective materials to reduce building solar energy uptake. Some cool roof materials also have high infrared thermal emissivity in order to reject thermal energy.
- **"Green Roofs"** are rooftops planted with vegetation, living vegetated systems that absorb sunlight. "Intensive" green roofs have layers of soil that are 15 to 30 cm thick or deeper to support a broad variety of plants. "Extensive" green roofs are simpler systems with a soil layer of 15 cm or less to support grass or other ground cover.

Energy-efficient roofs reduce space cooling energy consumption – thus reducing greenhouse gas (GHG) emissions – in most climates, and enhance occupant comfort where space cooling is not available (see detailed discussion below).

These impacts are especially important in urban areas where the concentration of people and space-conditioned buildings can increase ambient temperatures from 1C to 12C above surrounding areas. This local warming, termed the "Urban Heat Island" (UHI) effect, increases building space cooling energy consumption, summer peak electricity demand, and air conditioning costs. The UHI effect increases air pollution and greenhouse gas (GHG) emissions, causing heat- and pollution-related illness, and can harm water quality when water falling on heated impervious surfaces carries heavy minerals and other pollutants to ground water and natural ecosystems (US EPA, Heat Island Effect, 2014). With over 50% of the world's population living in urban areas today, and 66% expected to do so by 2050, energy-efficient roofs can play an increasingly important role in limiting energy consumption and GHG emissions (United Nations, 2014).

1.1.1 Cool Roofs

What is a cool roof and what does it do?

Cool roofs are a mature and proven approach for reducing building space cooling energy consumption – and corresponding GHG production. Cool roof technology is commercially available at little or no incremental cost compared with conventional roofing, for virtually every building roofing application and form factor:

- Residential, commercial, industrial and warehouse buildings (this Technical Report focuses on residential and commercial buildings).
- Low-sloped (<2:12 – a roof with less than 2 cm vertical drop for every 12 cm horizontal distance, or less than 9.5°) roofs (typically used for modern commercial buildings), including single-ply membrane, painted metal, built-up roofing, modified bituminous membrane, fluid-applied membrane, thermoplastic single-ply membrane, elastomeric single-ply membrane, polyurethane foam, and various coatings.
- Steep-sloped (>2:12) roofs (typical of residential and historic buildings), including asphalt shingle, tile (especially for historic buildings), slate, wood, and metal.

How does a cool roof impact climate change?

A cool roof impacts climate change primarily by reducing a building's space cooling load and associated GHG emissions. To reduce cooling loads, cool roofs employ highly reflective materials that cut building solar energy uptake. Some cool roofs also have high infrared thermal emissivity in order to better reject heat to the ambient.

In cities, highly-reflective cool roofs also help reduce the cooling loads of *all* buildings by increasing the "albedo" – literally "whiteness" – of the urban area, thus increasing reflection of solar radiation, which reduces local UHI effect warming and thus city-wide building space cooling energy consumption.

Roof "coolness" is most commonly measured by two parameters - "solar reflectance" and "thermal emittance": (ENERGY STAR; Cool Roof Rating Council)

- **Solar reflectance** is the fraction of solar energy received by a surface that is reflected by that surface (0.0 to 1.0).

- **Thermal emittance** is the ability of a material to radiate, or "emit", absorbed heat (0.0 to 1.0). The higher the thermal emittance number, the better the material is at releasing heat.

Some organizations, such as LEED, use a related combined metric, "**Solar Reflectance Index" (SRI),** which describes how the much a roof surface warms in comparison with a standard white roof under standard solar and ambient conditions. SRI can be measured experimentally:

$$SRI = (T_{black}-T_{surface}) / (T_{black}-T_{white}) \times 100$$

$T_{surface}$ is the temperature of the surface in question, T_{black} is the temperature of a black surface with reflectance of 0.05 and emittance of 0.90, and T_{white} is the temperature of a white surface with reflectance of 0.80 and emittance of 0.90, all under standard solar and ambient conditions (Akbari et al, 1996). SRI typically ranges from 1 to 100; however, extremely reflective products can have SRI ratings exceeding 100 (LBNL SRI Calculator). SRI can alternatively be calculated from measured solar reflectance and thermal emittance values as specified by ASTM E1980.

The ideal cool roof would have high solar reflectance and high thermal emittance – and correspondingly high SRI rating. It would reflect most incident solar energy and reject thermal energy to the ambient, and the roof surface would heat little. In practice, aesthetic concerns affect the materials that are selected, and dirt and aging reduce performance. As a result, steep-sloped roofs where appearance is important and "non-cool" materials such as asphalt shingles, clay tile, and corrugated metal are traditional, have lower standards – and lower performance – than less-visible low-sloped commercial roofs.

Table 1.1 illustrates some typical performance standards:

Table 1.1 Summary of cool roof requirements and definitions

Organization	Roof Type	Solar Reflectance (Initial)	Solar Reflectance (3 yr. Aged)	Thermal Emittance (3 Year Aged)	SRI (Initial)	SRI (3 Year Aged)
California Energy Commission (as of 2014)	Low Steep	N/A N/A	0.55 to 0.63 0.20	0.75 0.75	N/A N/A	64 10-16 (varies by location; calculated)
USGBC LEED v4	Low Steep	N/A N/A	N/A N/A	N/A N/A	82 39	64 32
US DOE (IECC 2015)	Low Steep	0.70 N/A	0.55 N/A	0.75 N/A	82 N/A	64 N/A
ENERGY STAR	Low Steep	0.65 0.25	0.50 0.15	N/A N/A	N/A N/A	N/A N/A

As Table 1.1 indicates, low slope roof initial solar reflectance standards average about 0.7. Three year-aged reflectance ratings, which seek to represent actual field performance, are required by most organizations and average around 0.6. Three year-aged SRI values are 64. Steep roof 3 year-aged reflectance standards are much lower, only about 0.20, with SRI standards of only 10 to 30.

What impacts do cool roofs have in practice? Table 1.2 presents some examples:

Table 1.2 Cool Roof Impact Examples

Description of Study (Author)	3 Year-Aged Solar Reflectance	Roof Temperature Reduction	Annual Roof Heat Gain Reduction	Building Cooling Energy Reduction
Meta-study of reflective materials applied to building components, using experimental measurement, test cells and simulation (Hernandez-Perez 2014)		5C to 10C typically; 2C to 15C range (test cells)	45% average; 9% to 70% range	30% to 40% typically; range from 2% to 80%
Compendium of strategies for reducing heat islands (US EPA 2008)	0.65+ vs. 0.05 to 0.15 for ordinary roofs	31C to 47C; cool roofs are typically within 6C to 11C of ambient	3.2 kWh/m^2** for California buildings	20% average; range from 20% to 40%
Simulation of multiple commercial building types throughout the US (Levinson & Akbari 2010)	0.55 vs. 0.20 for ordinary roofs	N/A	44%*** 5.0 kWh/m^2** average	N/A
Experimental and numerical assessments of various buildings in Greece (Gobakis 2016)	N/A		2.5 to 10 kWh/m^2** 6.3 kWh/m^2** average	20% to 40%
Hyderabad India study (NRDC 2018)		4C to 9C	20 to 22 kWh/m^2** vs. black; 13-14 kWh/m^2** vs. concrete	14% to 26% vs. black roofs; 10% to 19% for concrete roofs
Tile coatings that reflects IR to increase TSR* but retain visible appearance esp. for historic buildings in urban areas (Pisello 2013)	0.45 to 0.55 (visible 0.31 to 0.89; IR 0.66 to 0.90)	N/A	N/A	N/A
Polyvinylidene fluoride (PVDF) coating that reflects IR to increase TSR* but	0.55 average vs. 0.20 average for			10% to 30% (peak load)

Description of Study (Author)	3 Year-Aged Solar Reflectance	Roof Temperature Reduction	Annual Roof Heat Gain Reduction	Building Cooling Energy Reduction
retains visible appearance, even for dark colors (Tex-Cote 2012)	non-coated surfaces			

*TSR = Total solar reflectance. Infrared (IR) radiation comprises ~50% of solar energy, so coatings tailored to reflect IR only can reflect most solar energy with almost any visible color.
**Savings is stated per unit conditioned *roof area* (not floor area).
***The reduction of the roof's solar heat gain of 44% = (0.55-0.20)/(1-0.20)

As Table 1.2 illustrates:

- Cool roofs can reduce roof temperatures 10C or greater.
- Roof solar heat gains are reduced 40%+, corresponding with energy savings of 4-7 kWh/m^2, averaging 5.0 kWh/m^2 of conditioned roof area annually for typical locations (Levinson & Akbari, 2010; Graveline, 2014).
- This results in building cooling energy reductions of 10% to 20% or greater, depending on building height, insulation and other factors; typically ~20% for the floor below the roof (Global Cool Cities alliance, 2012).
- Cool coatings are available for tile roofs, especially for urban and historic buildings common in Mediterranean climates. Such coatings can be used on new tiles or applied to existing tiles. The appearance is virtually identical to traditional tiles.

Cool roofs do come with an energy price in the form of a "space heating energy penalty": In winter, when space heating is needed, cool roofs also absorb less heat from the sun than conventional roofs. Research shows that the heating penalty ranges from 1 to 4 kWh/m^2, averaging 1.89 kWh/m^2 (0.0645 therm/m^2) of conditioned space annually (Levinson & Akbari, 2010; Graveline, 2014). The space heating penalty is anti-correlated with space cooling loads – greatest in cold climates with high space heating loads and smallest in hot climates with small heating loads. So, the net result is that, depending on building location, design, orientation, internal loads, and energy costs, it pays to use cool roofs in hot and temperate climates, and not in very cold climates. Estimates are that cool roofs make sense on 80%+ of buildings; modest savings are achievable even in cities with cold winters, such as Minneapolis and Denver. The only exception is cold continental climate locations (Graveline, 2014).

What must be done at the agency level to implement cool roofs?

Cool roofs require little from the building owner in return for substantial gains:

For new roofs or replacement roofs, cool roof products are available as replacements for virtually every type of commercial or residential roof: Sheets, coatings, coated metal, asphalt shingles with IR-reflecting granules, clay tiles, concrete tiles, even slate and other materials (CRRC's directory of products and manufacturers). Installation is the same as conventional roofing and costs are similar (see below).

Table 1.3 illustrates what is possible, even for traditional tile roofing in virtually any color. Solar reflectance is increased on average 0.2 to 0.3 with no change in color. This is accomplished by coloring the tile using "cool pigments", either mixed integrally or applied in a surface coating.

Table 1.3 Cool Roof Tile Solutions

Tile Color	Conventional Tile Solar Reflectance	Cool Roof Tile Solar Reflectance	Increase in Solar Reflectance
Black	0.04	0.41	0.37
Blue	0.18	0.44	0.26
Gray	0.21	0.44	0.23
Terracotta	0.33	0.48	0.15
Green	0.17	0.46	0.29
Chocolate	0.12	0.41	0.29

Source: Akbari, 2006

Even without reroofing, cool roof upgrades can be performed economically (see financial discussion below) using standard painting practices and materials. Cool-roof coatings are available to upgrade most existing conventional low-slope roof types (membrane, coated, metal). And IR-reflective cool-roof coatings are available for upgrading steep-slope tile or metal roofs while minimally altering their visible appearance (e.g., Tex-Cote, 2012). Such coatings usually contain a PVDF or acrylic resin for surface protection and ultraviolet reflection, combined with special pigments that reflect IR but appear visibly colored. The coating process and equipment are standard painting coverage and gear (e.g., Tex-Cote, Reflec-Tec).

Whether for a new roof or a reroof, the economic cost of a cool roof is small (see the financial discussion below for more details). A 2014 survey of 22 US new roof and reroof projects found: (Sproul, 2014)

- Installation costs were the same as ordinary roofs - \$22/m^2
- Maintenance costs were the same as ordinary roofs - \$0.20/m^2/year.

- Cooling savings for a cool roof in comparison with an ordinary roof averaged $0.20/m^2/year (energy use in the floor below the roof was reduced 10% to 20%).
- Cool roof lifetime was the same as ordinary roofs - 20 years.

So to implement a cool roof, the building owner incurs no additional work, initial cost, increased maintenance cost, or loss of aesthetics. And the owner realizes a substantial cooling energy reduction and energy cost reduction.

1.1.2 Green Roofs

What is a green roof and what does it do?

Green roofs are rooftops planted with vegetation, living vegetated systems that absorb sunlight. Green roofs are classified as either:

1. **"Extensive" green roofs** are comparatively simple systems with a soil layer of 15 cm or less to support grass or other ground cover. Typically, extensive green roofs employ low-lying, hearty plants from the stonecrop perennial family, most commonly sedum. The main objectives of an extensive roof are to mimic the function and properties of a natural vegetative field or green space and to serve specific engineering functions, including thermal insulation and water retention. The most common extensive design comprises a single unirrigated layer of lightweight growth media with succulent plants and herbs. Such designs are durable and require little maintenance (Miller, 2015). Extensive roofs can provide water retention, thermal, and biodiversity benefits, as discussed in detail below.
2. **"Intensive" green roofs** have layers of soil that are 15 to 30 cm thick, or more, to support a broad variety of plants. Intensive green roofs, essentially roof gardens, comprise more plant material and organic substrate, are heavier, more costly, and require more maintenance (hence the name "intensive"), depending on the plants and design selected. But intensive green roofs, in addition to the functional benefits of extensive green roofs, provide rich design opportunities with increased flora and fauna biodiversity, and can serve as an attractive and valuable amenity for occupants.

Table 1.4 summarizes the functional subsystems and roof layers that comprise a typical extensive green roof: (Miller 2015)

Table 1.4. Extensive Green Roof Functional Subsystems and Layers

Functional Subsystems	Layers
• Aesthetic surface • Plant nourishment and support • Drainage • Protection of the underlying waterproofing system • Waterproofing system • Insulation system • Structural support	• Vegetation • Growing media • Filter fabric • Moisture retention / drainage panel • Insulation • Root barrier • Protection course • Waterproofing membrane (e.g., hot rubberized asphalt) • Substrate (e.g., concrete deck)

Source: Miller 2015; Drawdown analysis

Green roofs provide a wide palette of functions and benefits (Steven Peck, greenroofs.org Interview 2019; Miller 2015; Copenhagen 2016; EFB). These can be divided into two main categories:

- Functions directly impacting climate change, detailed in the next section: How does a green roof impact climate change?
- Other green roof functions and benefits are discussed below in Additional Benefits and Burdens.

How does a green roof impact climate change?

Green roofs impact climate change primarily by reducing building space cooling and space heating, and the associated GHG emissions. Green roofs reduce space cooling loads by reflecting sunlight to reduce rooftop heat gain much like cool roofs, and by providing a layer of thermal insulation. Green roofs reduce building space heating by providing an added rooftop insulating layer to help retain heat, and thus outperform poorly insulated cool roofs which suffer from the "space heating penalty" in this role.

In addition, green roofs provide a cooling effect through the process of "evapotranspiration" – evaporation of water from the green roof surface plus transpiration from the plants growing on it. The combination of shade provided by plants and evapotranspiration adds synergistic elements to cooling the building (US EPA 2008.). To a smaller degree, green roofs (like cool roofs) reduce space cooling energy consumption by reducing rooftop temperatures, thus reducing AC intake air temperature and increasing the efficiency of rooftop-mounted AC units.

In reducing building space cooling and heating, green roof performance is equivalent to a cool roof with solar reflectance of ~0.7 plus "substantial insulation". Insulating values are typically ~0.3 to 0.9 m^2K/W, but values vary widely depending on thickness, planting, moisture content and other factors (Berardi 2014; Santamouris 2014). Consequently, a green roof outperforms an uninsulated cool roof in moderate or cool climates, but a high-SR cool roof (>0.7) performs better in hot climates (Santamouris 2014).

So, overall, a green roof can be expected to provide space cooling energy consumption and rooftop temperature impacts comparable to those of a moderately-insulated, high-SR cool roof, as summarized in Table 1.2 Cool Roof Impact Examples. Annual roof heat gain for space cooling can be expected to be similar: ~5 kWh/m^2-year; one of the few experimental studies of this, conducted in a very hot Florida climate, found a green roof energy savings of ~1.6 kWh/m^2, noting that, "most commercial low slope roofs are significantly darker than the conventional roof used in this study" (Cummings 2007). Beyond such hard-to-find engineering measurements, estimates of green roof performance vary widely, depending on the details of the system simulated or measured. Some studies have found green roof cooling energy reductions similar to those of cool roofs, with superior space heating energy savings (Constanzo et. al. 2016), and others have found green roofs to have slightly better performance for both functions (Gagliano 2015; Sproul 2014). But generally, research shows green roof space cooling performance to be equivalent to that of a white roof, and space heating performance to be slightly better. Additionally, since green roof space heating impact is essentially that of thermal insulation, existence of other rooftop insulation *diminishes* green roof value for this function (Sailor 2012). Conversely, green roofs can have significant impact when installed in poorly insulated older buildings (Castleton 2010).

Green roofs also help to reduce GHG emissions indirectly: Green roofs with SR of ~0.7, by reducing rooftop temperatures, can increase the efficiency of rooftop-mounted photovoltaics (whose efficiency goes inversely with temperature) and also help to mitigate the urban heat island (UHI) effect, thus increasing comfort and reducing air conditioning costs of nearby buildings (Santemouris 2014). But it appears that there is not adequate data to quantify the impact of green roofs on UHI (Berardi 2014; US GPA 2011). Green roofs help control storm water runoff by capturing rainwater, especially during peak rainfall events, reducing sewer capacity requirements and indirect GHG emissions. Such rainwater capture also improves water quality by reducing storm water overflow into urban sewage systems.

Green roofs can impact climate change in one fascinating way: As living vegetation, green roofs are unique among building systems in their ability to impact climate change directly by sequestering atmospheric CO_2. The literature on this topic is limited. In the first peer-reviewed article reporting an in-depth experimental investigation, Getter et. al. evaluated the carbon sequestration potential of 12 extensive green roofs composed primarily of Sedum species, with substrate depths from 2.5 to 12.7 cm, in

Michigan and Maryland, finding that, on average, the green roof sequestered 275 gC/m^2 over two growing seasons, i.e., ~138 gC/m^2-year (Getter et. al. 2009). The team acknowledged the limits of such systems, noting that "this ecosystem will not likely sequester large amounts of carbon due to the types of species used and shallow substrate"; the team also noted that a green roof has a "carbon cost" in terms of its manufacture and components (ibid).

Heusinger and Weber, much more recently, using the "eddy covariance method" to assess the potential of an extensive green roof in Berlin, Germany, found carbon sequestration of 313 gCO_2/m^2 year, equivalent to 85 g C/m^2 year, roughly comparable to the results of Getter et al. (Heusinger and Weber 2018).

Other research on intensive green roofs has found much higher levels of sequestration. Whittinghill et. al., in several experiments with irrigated green roofs, found carbon sequestration levels after three growing seasons that ranged from 4.7 to 65.3 kgC/m^2 – more than an order of magnitude greater that the results of Getter et al. (2014).

So, neglecting "carbon costs", the experimentally-observed direct sequestration by green roofs is ~100 gC/m^2 for non-irrigated extensive roofs, and possibly much greater for intensive systems.

Direct sequestration, thus, is a subject that bears further inquiry. Depending on electricity source, the quantity of carbon sequestered is not negligible in comparison with CO_2 reductions due to space heating / cooling energy reductions: Assuming average electricity CO_2 emissions of ~580 gCO_2/kWh (580 $kgCO_2/MWh$), and AC efficiency of ~3, each $kWh_{Thermal}$ of space cooling contributes ~193 [580/3] $gCO_2/kWh_{Thermal}$, or 54 $gC/kWh_{Thermal}$. The average space cooling roof heat gain reduction from Table 1.2 Cool Roof Impact Examples is 5.0 $kWh_{Thermal}/m^2$ of roof area, which translates to ~269 [54x5.0] gC/m^2 of roof area. The space heating energy savings due to green roof insulation has a similar order of magnitude, depending on location. So, while there is concern that "carbon costs" of materials, maintenance, irrigation, etc. may outweigh direct carbon sequestration benefits, the experimentally-observed direct carbon sequestration impact of ~100 gC/m^2 – or much greater – is the same order of magnitude as the space cooling / space heating impact, and thus makes a significant contribution to the total GHG impact of green roofs that cannot be ignored.

What must be done at the agency level to implement green roofs?

Building owners need to meet special requirements in order to obtain the benefits that green roofs offer:

As living systems, green roofs must meet specialized design requirements: Waterproofing is essential to protect the underlying building, and drainage mats are typically employed to slow the flow of water toward the drains in order to increase water uptake by soil and plants, and to reduce storm surges (Moseley 2013).

Roof slope is usually limited to less than 2.5:12 (11.8°, 21%), otherwise supplemental measures are required to prevent sliding instability. But steep roofs, up to 80% slope (~39°), are possible using special honeycomb supports or other approaches to prevent shear. A famous example is the Vandusen Botanical Garden Visitor Centre in Vancouver, Canada (Linda Velazquez greenroofs.com Interview 2019).

Green roofs need to comply with code requirements for wind resistance and structural loading, typically ASCE 7 and ANSI/SPRI RP-14 Wind Design Standard for Vegetative Roofing Systems. And green roof structural design needs to address substantial incremental dead loads, as well as live loads from moving water and from human occupants in accessible spaces. In the US, green roofs are usually regulated using existing standards for ballasted roofs; the most comprehensive guidelines for green roof construction worldwide is the German "Guideline for the Planning, Execution and Upkeep of Green Roof sites", which addresses weight, moisture, nutrient content, and other factors; and also certifies test laboratories (Miller 2015).

Green roof building owners also face higher installation and maintenance costs as compared with cool roofs or conventional "black" roofs: Table 1.5, based on a 2014 survey of 22 US new roof and reroof projects, compares green roof costs and lifetime with cool roofs and conventional roofs. As Table 1.5 illustrates, green roofs can last much longer than cool roofs or conventional roofs, but building owners face an incremental first cost of \$35 to \$150/m^2 or more and increased annual maintenance cost of up to \$2.70/m^2.

Table 1.5. Comparison of Green Roof Costs Vs. Cool Roofs and Black Roofs

Cost Factor	Green Roof	Cool Roof	Conventional Roof
First installation cost (\$/m^2)	Extensive: \$90 to \$260 Intensive: \$200 to \$430 and higher	\$22 to \$26	\$22
Replacement cost (\$/m^2)	\$57	\$22	\$22
Maintenance cost (\$/m^{2}year)	\$0.40 to \$2.9	\$0.2 to \$1.0	\$0.2
Disposal cost (\$/m^2)	\$1.3	\$0	\$0

Cost Factor	Green Roof	Cool Roof	Conventional Roof
Roof life (years)	40	20	20
Roof Additional Weight (kg/m^2)	Extensive: 50 to 150 Intensive: 150 to 200 and higher	N/A	N/A

Source: Sproul et al 2014; Linda Velazquez greenroofs.com Interview 2019; EFB; Berardi et al 2014; Moseley 2013; Castleton 2010

1.2 Adoption Path

1.2.1 Current Adoption

Cool Roofs

Drawdown estimates the global 2014 current adoption of Cool Roofs as ~2.17 billion m^2 roof area, and 5 billion in 2018 (or 5% of Cool Roof TAM, based on Project Drawdown projections from US DOE 2016, Shickman 2019, EPA 2008, Transparency Market Research 2018, and Grand View Research, 2019).

For cool roofs, the US market is considered "mature", the European market "established", and the rest of the world as an "initial market" (IEA Technology Roadmap, 2013). Cool roofs are most prevalent in the USA where they comprise ~25% of installed commercial roofs and ~5% of residential roofs, or ~10% of overall roof area: As of 2006, cool roofs represented 25% of ENERGY STAR manufacturer commercial shipments and 10% of their residential shipments; as Table 1.6 illustrates, cool roofs represented 21% of installed US commercial roofs in 2012, and today cool roofs represent ~60% of US commercial membrane roof installations (EPA Cool Roofs 2008, Shickman Personal Correspondence 2019).

Table 1.6 US Commercial Building Cool Roof Adoption 2012

Parameter	Value
Roof area estimate (million m2)	5,142
Floor area / roof area	1.57
Cool roof area (million m2)	1,085
Cool roof percent of roof area	21.1%

Source: US DOE CBECS 2016; Drawdown calculation

A major factor contributing to US cool roof leadership and market growth is that much of the original research and cool-roof materials development occurred in the US, especially at Lawrence Berkeley National Laboratory and its industrial partners. The US-based Cool Roof Rating Council (CRRC) was created in 1998 to develop methods for evaluating and labeling the solar reflectance and thermal emittance of roofing products. And several US states and many cities have had cool roof rebate or incentive programs, and cool roof building standards, for decades. Key success factors are discussed in depth below under "Trends to Accelerate Adoption".

European market adoption of cool roofs is "established" but early stage: The energy-saving potential of cool roofs and the role they can play in European energy policies are recognized. But the European Cool Roof Council (ECRC) (analogous to CRRC) was created only in 2011, as a result of an Intelligent Energy Europe (IEE) project, with the objective to "develop scientific knowledge and research in relation to 'cool roof' technology and to promote the use of cool roof products and materials in Europe, including developing a product rating programme for such products and materials" (ECCR website). But ECRC's rating program was not launched until 2015. And the strategic objectives of ECRC (as of 2016) illustrate the early stage of European cool roof efforts: 1) Formulation of cool roof product rating program in Europe 2) Inclusion of cool materials in European standards and energy assessment methods 3) Promotion of the benefits of cool materials to engineers and other stakeholders (Gobakis 2016). Today the European market is growing but fragmented (Transparency Market Research).

Indian market adoption of cool roofs is embryonic but has been gaining momentum over the last 10 years. Though India lacks a cool roof rating council (as of 2018), efforts are underway to establish one. And several building rating systems used for high-end commercial buildings in India, including LEED, GRIHA, and the Indian Green Buildings Council (IGBC), highlight cool roofs as a key strategy for reducing building energy consumption. Importantly, the Energy Conservation Building Code 2017 requires commercial building roofs to have a minimum solar reflectance of 0.6. And India has many city-level cool roof initiatives and pilot projects (Table 1.2 references one Hyderabad project). The need is great: 60% of roofs in urban India are galvanized metal, asbestos or concrete, exacerbating the UHI effect. Though only 5% of urban buildings have air conditioning today, 45% of all residential electricity is used for cooling homes (AC, fans, evaporative coolers, etc.). And the future need is likely to be far greater if, as expected, AC growth in India follows the pattern of China where urban room air conditioner penetration rose from 0.05 per household in 1995 to over 1.3 per household in 2012, as the country developed (NRDC 2018). Cool roofs can play an important part in this future, both to reduce energy consumption and GHG emissions and to foster comfort and health for occupants in the vast majority of buildings that lack space cooling altogether.

In China, where the market is embryonic, (as of 2014) the value of cool roofing is recognized, and some national and local building energy efficiency standards recommend, but do not require, cool roofs. In the past, national standards required the use of cool roofs on residential buildings in hot summer/warm winter climates, but they only "recommended" the use of cool surfaces on some other buildings (Gao 2014). But since 2011, cool roof adoption has advanced as standards and green roof test protocols have been established. By 2015, eight provinces or municipalities in hot summer regions had added cool surfaces credits to their building design standards. *JGJ/T 359-2015: Technical Specification for Application of Architectural Reflective Thermal Insulation Coating* is the first standard that offers cool coating credits (insulation trade-offs) for both public and residential buildings in all hot-summer Chinese climates (Hot Summer/Cold Winter; Hot Summer/Warm Winter). Potential future improvements to the current Chinese standard system include the development of a solar reflective material natural aging system and a revision of the laboratory aging process (Ge and Levinson 2016). So, the Chinese cool roof (and cool surface) market, though still young, is maturing and growing rapidly.

Summarizing current adoption: Cool roofs are established in the US, and growing in Europe, India, China and other countries, following to a large degree the roadmap developed in the US 20 years ago. Adoption has been propelled by favorable economics in low-slope roofs, especially single-ply membranes, where installation cost and maintenance cost premiums are zero or small; establishment of test protocols, rating systems, and standards; as well as development of products "tuned" for local needs.

Green Roofs

Drawdown estimates the global 2014 current adoption of Green Roofs as ~150 million m^2 and that for 2018 at 198 million m^2 (or over 1% of Green Roof TAM, based on Project Drawdown projections from EFB2015, greenroofs.com 2019, Velazquez 2019, Green Roofs for Healthy Cities 2017, US DOE 2012, Castleton et al 2010). The European Federation of Green Roofs and Walls (EFB) estimated the 2014 European Green Roof stock as 95.5 million m^2, with 11.3 million m^2 of new Green Roofs each year, an annual growth rate of about 12% (EFB 2015). With Europe ~2/3 of all Green Roofs, that would make the 2014 global Green Roof stock ~150 million m^2.

Beyond EFB's report, it is difficult to estimate green roof market adoption, since most data is at best regional. The greenroofs.com project database, perhaps the most comprehensive industry database – though with primarily a North American focus – now lists ~1700 projects totaling ~4 million m^2 of roof area. But these projects are estimated to represent only ~5% or less of worldwide green roof installation. which would make total global adoption ~80 million m^2 (greenroofs. com 2019; Velazquez 2019).

Most reports on green roof market adoption are localized and anecdotal: Germany, the world leader in green roof adoption, is said to have 14% of all flat roofs "greened" (Castelton 2010). The US DOE estimated ~300,000 to 400,000 m^2 of green roofs installed in North America (about 2/3 in the US) each year between 2004 and 2010 (US DOE 2012). The North America-oriented Green Roofs for Healthy Cities 2016 industry survey found ~400,000 m^2 of green roofs installed in 2016, which it characterized as understating the market by 25% to 50% (Green Roofs for Healthy Cities 2017). As of 2011, the US General Services Administration managed ~80,000 m^2 of US government building green roofs in the US (US GSA 2011).

Based on the data that is available, top venues for green roofs include historical leaders, Germany, where the "green roofs movement" started and, more recently, Denmark, followed by the whole of Western Europe, due to strong government policies and incentives (discussed in "Trends to Accelerate Adoption").

North American top cities, as of 2016, included Toronto, Chicago, Washington, DC, Philadelphia, Seattle and others (Green Roofs for Healthy Cities 2017).

In Asia, Singapore is a strong supporter and implementer (see "Trends to Accelerate Adoption"). Only a handful of the Greenroofs.com database projects are in Asia, primarily Singapore, China, and Japan (greenroofs.com).

1.2.2 Trends to Accelerate Adoption

Cool Roofs – Trends to Accelerate Adoption

Cool roofs are very attractive economically in hot climates – ASHRAE climate zones 1-3 – and are usually economical (after subtracting the space heating penalty) in climate zone 4 and perhaps in zone 5 and beyond (Pearson 2014). So, there certainly is potential for continued growth in warmer parts of the US and Europe, and for accelerated growth in hot developing regions, including India, China, and throughout the rest of South Asia, as well as in Africa, and parts of South America.

But what are the "key success factors" that have propelled cool roof adoption to date – especially in the US, the only mature market in the world today? How will these factors be tempered by local conditions and needs as cool roofs are adopted in other countries in the future? Especially, what must be done to achieve broad global adoption?

To shed light on what is needed to accelerate adoption of cool roofs, it is valuable to examine the adoption of cool roofs to date. Table 1.7 summarizes some of the key success factors that have driven US cool roof growth:

Table 1.7 Cool Roof Key Success Factors for US Market Adoption

Cluster	Key Success Factors
Technical Functional Performance	• Establish the possibility / prove experimentally that reflective roofs result in reduced cooling loads / demonstrate the basic parameters of benefit (solar reflectance and emissivity) (Akbari 1996) • Quantify the benefits: When and where do cool roofs make sense? What is the payoff? (Levinson & Akbari 2010) • Develop commercial cool roof materials via academic-industry collaboration (Akbari 2006) • Design effective implementation programs • Establish test methods, rating systems, and standards for evaluating practical cool roof materials so that customers can confidently evaluate cool roof products (ENERGY STAR, Cool Roof Rating Council) • Run pilots to validate and demonstrate real-world installation feasibility and functional performance
Economic Value	• Establish economics in real-world application • Provide incentives and rebates • Voluntary "green" standards for awareness, education, and economic benefit (e.g., LEED, ENERGY STAR)

Social and Political Leadership	• Political leadership that:
	  ○ Provides the will and vision to drive cool roofs
	  ○ Brings stakeholders together, build consensus and commitment
	  ○ In some cases, creates building standards and requirements
	• Government mandatory codes and standards (e.g., California Title 24; local building codes)

Source: Drawdown Analysis & Sources as Noted.

As Table 1.7 illustrates, three classes of factors have contributed to US cool roof success:

- **Establishment, *in some cases development*, of technical functional performance and real-world feasibility.** Technical "proof of concept", development of cool roof materials, and demonstration of economic benefit was originally spearheaded by Lawrence Berkeley Laboratory and Oak Ridge National Laboratory and supported by the US Department of Energy. This work has proven central to US commercialization of cool roofs over the last 20+ years. In addition to this research and development, the US government also played a key role through the ENERGY STAR program which provides clear, unbiased standards and visibility for commercial cool roof products, and by conducting cool roof pilots on government buildings (see discussion below).
- **Demonstration of economic value**. Likewise, a critical step toward growth of cool roof adoption in the US was establishment of test methods, rating systems, and standards so that customers can

confidently assess the benefits and value of cool roof products. The prime example of this is the Cool Roof Rating Council, "created in 1998 to develop accurate and credible methods for evaluating and labeling the solar reflectance and thermal emittance…of roofing products" (CRRC website).

- **Social and political leadership**. Beyond the role that the US government played in supporting initial cool roof R&D, local-level government leadership has played a key role in US cool roof implementation: Most cool roof adoption in the US is urban and most programs in the US have operated at the city level (see examples below). Urban leaders who have successfully advanced cool roofs in their city have, first, established a strong vision of the need to address heat and energy efficiency. They have brought together stakeholders outside and inside government to develop an integrated strategy and consensus for executing it, and implemented government programs, including a benefits assessment (which buildings to target; which benefits, e.g., energy costs, peak electric loads, UHI effect), evaluation/establishment of alternative cool roof programs such as voluntary rebates, incentives, and in some cases, migration to mandatory standards to foster cool roof implementation. Key stakeholder partners include: (Kurt Shickman personal communication 2019)
    - City departments impacted (Finance, Health, Emergency Response, Public Works and other). Linkages to other government programs, such as health and emergency response are key.
    - Academic institutions who can perform unbiased analyses.
    - Developers.
    - Business, civic, and other community organizations.

What social/political initiatives have worked? Table 1.8 illustrates the approaches and specific programs employed by many US states and numerous cities. These can be organized into three main approaches (that are now being emulated in other countries around the world today):

- Rebates and financial incentives
- Voluntary standards
- Mandatory codes and standards

Table 1.8 Examples of US Cool Roof Programs

Approach	Program Examples
Rebates and Financial Incentives	• California: Several cities and electric utilities • Colorado: Fort Collins • Florida: Orlando

Approach	Program Examples
	• Idaho: Electric utility • Illinois: Chicago • New Jersey: Electric utility • New York: Electric Utility • Oregon: Electric utility • Texas: Two cities and electric utility • Others: Utah, Wyoming
Voluntary Standards	• ENERGY STAR • LEED Rating Systems • Green Globes
Mandatory Codes and Standards	• Arizona: LEED silver for state buildings • Arkansas: 2003 IECC for residential; ASHRAE 90.1 for commercial buildings • California: Title 24 2016 • Illinois: Chicago Energy Conservation Code • Florida: Florida Building Energy Code mandatory statewide for residential buildings • Georgia: Georgia Construction Code (IECC 2009; ASHRAE 90.1) mandatory statewide for commercial buildings • New York: New York City Energy Conservation Code (ASRHAE 90.1) mandatory for all new buildings and alterations • Texas: State Energy Conservation Office (IECC and ASHRAE 90.1) mandatory for commercial and state buildings • United States: Commercial buildings cool roof required in climate zones 1, 2, 3 (some exceptions). 24 states have mandatory codes of varied scope, based on IECC and ASHRAE 90.1.

Source: CRRC 2017

As Table 1.8 illustrates, rebates and incentives are common, if not universal. These have ranged from \$3 to \$5/m^2 for utility programs, which are often are narrowly focused on reducing peak electricity loads and not been too impactful, to \$10 to \$50/m^2 for more holistically focused city-run programs, which have been (Shickman personal communication 2019).

Voluntary standards, especially ENERGY STAR and LEED have been key:

- **ENERGY STAR,** operated by the US EPA and US Department of energy, sets product criteria and qualification standards for steep-slope and low-slope cool roof surface solar reflectance. Only those roof products that meet the specifications listed may qualify as "ENERGY STAR qualified" (ENERGY STAR). Despite its success, the US government under the current (2019) administration has recently proposed "sunsetting" the ENERGY STAR roof products specification in three years because "a recent review performed by EPA indicates that it has been surpassed, in many instances, by commercial building codes and that the range of considerations relevant to the residential purchase decision mean homeowners would be better served by a different kind of resource" (ENERGY STAR 2018).

- **Leadership in Energy and Environmental Design (LEED) "**is the U.S. Green Building Council's voluntary green building certification system. Under LEED Version 4, the following rating systems award up to 2 points for heat island reduction under the Sustainable Sites Credit: Building Design and Construction (BD+C), Building Operations and Maintenance (O+M), Neighborhood Development (ND), and Homes. LEED Interior Design and Construction (ID+C) awards up to 1 point under Innovation: Heat island reduction. When cool roofs are used for the heat island reduction credit, the CRRC Rated Products Directory can be used to find products that meet the requirements" (CRRC 2016).

Mandatory codes of varying scope are established in at least 24 states. Many of these are based on IECC and ASHRAE 90.1 standards. Probably the first, most important and most impactful mandatory standard is California's Title 24:

- **Title 24** ("California's Building Energy Efficiency Standards for Residential and Nonresidential Buildings: (Title 24, Part 6)") "contains requirements for the thermal emittance, three-year aged reflectance, and Solar Reflectance Index (SRI) of roofing materials used in new construction and re-roofing projects. The requirements apply to new construction and to retrofits or additions that replace or re-coat at least 2,000 ft2 of roof space for nonresidential buildings and 1,000 ft2 of roof space for residential buildings, or 50 percent or more of the roof surface (whichever is larger). These requirements apply to nonresidential, high-rise residential, and low-rise residential buildings across California's 16 climate zones. Additionally, roofing products used for meeting the Title 24, Part 6 requirements must be rated and labeled by the CRRC (see section 10-113 of Title 24, Part 6)" (CRRC). Title 24's origin dates to California's first building energy efficiency standards in 1978, California Energy Commission Building Energy Efficiency Standards, Title 24 of the California Code of Regulations (known colloquially as "Title 24"). It was implemented to govern the new construction of buildings within the state. In October 2005, cool roofs became a permanent requirement within California's energy code.

While California is the adoption leader in the United States, implementation is now common throughout the US, especially in the south. Cool roof incentives and standards are also prominent in major cities, such as New York City, Los Angeles, Chicago and many others (CRRC). Interest and standards establishment is on the rise in Europe (Zinzi and Romeo 2010), India (NRDC 2018), and China (Gao 2014).

Going forward, similar technical, economic and social/political success factors will likely drive cool roof adoption – in fact, as illustrated above, this is already happening in Europe, India and China. What is different today is that the core technical and economic work has been done. Future success will increasingly hinge on the ability of countries to develop and implement at mass scale cool roofing materials suited to local needs. The evolution in Europe and other developed countries, where buildings and economic conditions are similar to the US, will likely follow a trajectory similar to US development.

Cool roof implementation in the developing world is likely to have some parallels – drawing on proven technical success and economic models – but the details will likely be quite different: China has conducted the techno-economic research (Gao 2014) and has begun developing standards (Ge & Levinson 2016), in fact working with some of the LBNL researchers who have driven the US cool roofs effort. But, given the approach China has taken in heat pump, air conditioning, and district heating, incentives and standards are likely to be more uniform than in the US, at least on a climate zone basis.

India and other developing countries, likewise, have done the spade work but face two new challenges that will drive the nature of cool roof implementation:

- **Implementing cool roofs for low-income communities:** "An estimated 65 million Indians live in urban, low income communities with little or no access to adequate housing, electricity or other urban services." At the building level, by lowering factory and workplace temperatures, cool roofs can significantly improve health by reducing heat-related illness, increase economic output, and increase comfort. And cool roofs help reduce the UHI effect city-wide. But first cost is a huge barrier for low-income people. So, finding low-first-cost solutions suited for buildings in low-income communities (corrugated metal, concrete, or asbestos roofs) and that use locally-available materials will be critical for addressing these needs. These may be as simple as white paint or lime wash (at a cost of only $0.7/m^2 though it must be repainted frequently) (NRDC 2018).
- **Addressing rapidly growing demand for space cooling comfort:** As discussed above, air conditioning implementation in India and other developing countries is expected to follow a very rapid growth path much more similar to that of China than to that of the US. Such growth will rapidly increase electricity consumption and stretch peak generating capacity. If the first cost barrier can be overcome, cool roof implementation has the potential to reduce or delay the need for additional generation capacity.

Green Roofs – Trends to Accelerate Adoption

With a high first cost and a broad palette of benefits – not all of which can be captured by the building owner – green roof adoption depends on communities recognizing, and rewarding or mandating, their use. Key trends and key success factors needed to accelerate adoption of green roofs include:

- **Supportive government policies, regulations and incentives.** Because of their high cost and maintenance expense in comparison with other roofs, supportive government policies, regulations and incentives have been essential for green roof growth: The cities and countries with widespread implementation have provided financial incentives and building mandates. Copenhagen, Denmark is a leading example: Driven originally by a 2008 search for alternatives to handle rainwater and wastewater, Copenhagen in 2010 made it mandatory for all new flat roofs to have a green roof installed as part of the building's climate-change preparedness strategy. As of 2016, this regulation had resulted in over 40 green roofs totaling 200,000 m^2 (Copenhagen 2016). In Germany, over 90 cities require green roofs in certain building and at least 48 cities provide financial support for green roofs; as of 2016, Germany had installed 86 million m^2 of green roofs, accounting for 14% of Germany's roof area (Copenhagen 2016; Linda Velazquez greenroofs.com Interview 2019). In North America, a 2009 Toronto regulation required green roofs on new residential, commercial, or institutional buildings with over 2,000 m^2 roof area (industrial buildings have a different requirement). Toronto also provides financial incentives up to \$50/m^2, subject to certain limits. As a result, in a marked departure from previous years, in a 2016 survey of green roof installers, Toronto beat Chicago, Washington DC, Seattle and other North American cities to become the number one in green roof installations, with over 60,000 m^2 installed that year (Green Roofs for Healthy Cities 2017). Several major US cities incent green roofs: Chicago, with over 500,000 m^2 of green roofs accepts green roofs as meeting its solar reflectance requirement. New York City offers a 1-year property tax reduction of ~\$48/m^2. And Washington DC's "20-20-20" plan seeks to create 20 million ft^2 (2 million m^2) of green roofs, representing 20% of city building roof area over the next 20 years. In China, Shanghai has run a campaign fostering green roofs since 2003, resulting in 50,000 m^2 by 2008; Beijing, with various policies and programs promoting green roofs, as of 2008 had 1 million m^2 installed, with 100,000 m^2 being added annually (Copenhagen 2016). Berardi has summarized examples of urban policies promoting green roofs (Berardi 2014).
- **Uniform design, construction and maintenance standards and guidelines.** The German Landscape Research, Development, and Construction Society (FLL), established in 1975, is an

independent non-profit organization that has been working on green roof standards for more than 30 years. The FLL's "Guideline for the Planning, Execution and Upkeep of Green-Roof Sites" (FLL Guideline) reflects the latest developments in German acknowledged state-of-the-art technology, and, thus, is a valuable tool for the construction of reliable, high-quality green roofs worldwide (Breuning 2019). The FLL Guidelines provide widely-used, *but far from universally-applied*, standards and guidelines addressing all aspects of green roofs, including: (Breuning and Yanders 2008)

  - Planning: Standards, types of systems, green roof functions, and especially construction and technical requirements, such as roof slopes, design loads, drainage and watering, accessibility, root resistance, protection from mechanical impact, construction of roof outlets, waterproof membranes, fire resistance.
  - Execution: Vegetation area drainage and support; storm water retention, storage and discharge; seeds, plants and vegetation; stability and erosion protection.
  - Maintenance: Tasks that need to be performed, consistent with the greening method, establishment of the maintenance plan and contract, and warranties.

- **Recognition of green roof non-energy benefits, such as stormwater management.** Many of the regulations and incentives described above were implemented to help manage stormwater. Green roofs can absorb 50% to 80% of annual rainwater, delaying flow to storm drains, and avoiding overflowing sewer systems. Rainwater is also often harvested for irrigation. Water management has been a major driver in green roof programs in Copenhagen, Toronto, Düsseldorf and other German cities, Chicago, Portland, Philadelphia, Washington, DC, and many others.
- **Active promotion and visibility.** Promotion by and visibility by voluntary organizations such as LEED, as well as promotion by business leaders and government organizations, have been essential. The US General Services Administration (GSA), for example, as of 2011 maintained 24 green roofs and routinely installs green roofs on new and existing buildings. As part of its responsibility for managing US government facilities, GSA has conducted in-depth analyses of green roof costs, benefits and challenges (GSA 2011). GSA analysis has enlightened many private projects. A high-visibility private sector green roof example is the 9-acre green roof atop Facebook Building 20 in Menlo Park, CA, which contains 400 trees and a half mile walking loop (Facebook 2019).
- **Appreciation of green roof aesthetics.** Green roof adoption has grown in cities that appreciate the green roof aesthetic. Singapore, for example, bills itself as "A City in a Garden" (Singapore 2014).

- **Appreciation of the value of biodiversity.** Green roofs support biodiversity by creating habitats for animals and plants. Many cities, including Copenhagen, Sydney, Australia, and Basel, Switzerland have integrated green roofs into their strategies for biodiversity (Copenhagen 2016).
- **Consideration of lifecycle cost.** Green roofs have a high first cost but can be economically attractive on a lifecycle cost basis, especially if non-energy impacts are valued.
- **Establishment of a base of skilled installation and maintenance professionals.** As a living system with a unique aesthetic, a green roof faces unique design, implementation, and maintenance challenges: Compared with conventional roofs, green roofs are much heavier, including dynamic loads from water and people, are structurally more complex, and require more sophisticated waterproofing solutions. Addressing these requirements requires a strong base of designers and architects, engineers, installers, and maintenance professionals skilled in green roof technology.

1.2.3 Barriers to Adoption

Cool Roofs

With technical feasibility and economic viability proven (at least for developed countries), the key barriers to future cool roof adoption include:

- **First cost vs low energy prices.** As discussed above, first cost can be an insurmountable barrier for low-income communities in developing countries. But even in affluent developed countries, despite the proven economic viability of cool roofs, a first cost increment of only a few percent can be a significant barrier, absent a mandatory code or financial incentive. This barrier is similar to that faced by other energy efficiency measures, such as thermal insulation, in affluent countries with low energy prices. First cost is especially a barrier in residential buildings where "spec" construction, driven by first cost, is common, and lifecycle cost analysis is rare (Shickman personal conversation 2019).
- **Customer education and awareness.** For high-end commercial buildings cool roof awareness – and market adoption – are high. In such buildings, designed by top architects and managed professionally, life cycle financial analysis is common and the visibility of a program such as LEED can command a premium from tenants. But in lower-tier commercial and residential buildings, and more so in low-income communities, the economic, ecological, and comfort benefits of cool roofs are poorly appreciated; much less "co-benefits" such as reducing the UHI effect.

- **Lack of professional experience.** US experience over the last 20+ years and the slow ramp of cool roofs in Europe and China illustrate the time it takes to establish test methods, rating systems and standards; get products to market; gain performance credibility; and get designers, roofers, and others in the construction trades to employ cool roofs.
- **Political commitment.** As the national examples discussed above illustrate, it can be difficult – and take many years – to establish a national policy pathway for cool roofs. The EU is moving forward, albeit at a deliberate pace (considering how long cool roof knowledge has been available). Both China and India are advancing, but still represent very low adoption. And in the US, which pioneered cool roofs and where many state and local incentive/standards programs are in place, the federal government under the current administration is backtracking on cool roofs and other energy efficiency initiatives.

Green Roofs

Key barriers to green roof adoption include:

- **High installation and maintenance costs.** As Table 1.5 illustrates, green roofs can last much longer than cool roofs or conventional roofs, but building owners face an incremental first cost of \$35 to \$150/m^2 or more, and increased annual maintenance cost of \$2.70/m^2. Green roof installations have a significant economy of scale. But overall, in addition to the first-cost barrier that confront most energy efficiency measures, such as cool roofs, green roofs face an additional financial hurdle that cannot be addressed by lifecycle assessment of energy benefits alone. Green roofs, thus, require either government incentives and mandates, or valuation of non-financial benefits, to overcome this barrier.
- **Lack of supportive government policies, regulations, and incentives.** As illustrated above, many cities and countries have supported green roofs with mandates and incentives that have been essential to success. But such policies are far from universal, especially in less-wealthy developing countries, and their absence is a huge barrier to green roof adoption globally.
- **Lack of uniform design, construction and maintenance standards and guidelines.** Detailed industry standards and guidelines have been central to green roof success (see key success factors discussion of the German FLL Guideline). And conversely, *lack of standards* is a top barrier to wide-scale implementation and cost reduction of green roofs in many countries, including the USA, where even though the FLL Guideline is widely accepted, most projects are custom made solutions – unlike Germany where green roofs are highly standardized (Philippi 2016; Greuning 2019). Additionally, ASTM standards for commonly-accepted definitions, requirements, and test

methods for materials and practices are missing (Philippi 2016). So, lack of uniform standards and guidelines is a major barrier for green roofs in most countries.

- **Lack of experienced and educated design, engineering, installation, and maintenance professionals.** As living systems, green roofs require unique design, installation, and maintenance skills. There is a gap between traditional roofing industry contractors – who typically are not skilled at installing green roofs – and green roof designers and contractors, and need for greater experience and education among green roof contractors and maintenance peopl. (Velazquez greenroofs.com Interview 2019).
- **Lack of customer awareness, education, and appreciation of the non-energy benefits of green roofs.** With much of green roof value associated with attributes that don't contribute directly to building cost reduction, education and appreciation of green roof benefits, such as storm water retention, aesthetics, and biodiversity, are critical. This barrier highlights the value of high-visibility public and private projects for customer awareness and education.
- **Unsuitability of the existing building stock.** Many existing buildings cannot bear the additional weight of a green roof, especially an intensive design. And, though green roofs can be installed on steep pitched roofs, doing so is difficult and costly. So green roofs are most easily installed on new low-sloped roofs. This highlights the importance of green roof building standards and codes to ensure that future buildings are suited for green roof installation.
- **Climate**. Green roofs are difficult to apply in very cold climates. And desert applications require irrigation, reducing the climate impact.

1.2.4 Adoption Potential

Cool Roofs

Cool roofs make economic sense on every building for which the cooling energy savings and comfort benefit outweighs the heating energy penalty plus any incremental cost associated with the cool roof. Roughly speaking, this equates to ASHRAE climate zones 1 to 5 (Pearson 2014), making the 2014 total addressable market (TAM) for cool roofs an estimated 100 billion m^2 (See Total Addressable Market below).

Green Roofs

Published insights into green roof adoption potential are scarce. The main constraints are building structural integrity to support the additional weight and Green Roof first cost. For example, Castleton has concluded that ~15% of existing UK service-sector buildings could be retrofitted (Castleton 2010). This report estimates the 2014 Green Roof TAM as approximately 15 billion m^2 (See Total Addressable Market below).

Current adoption has been driven largely by stormwater retention benefits, due to the municipal costs of maintaining storm water management infrastructure; increasingly, climate change is becoming a driver. So, it is reasonable to anticipate that green roof installations will continue at current rates, adding at least 5 to 10 million m^2 annually in places like Germany, North America, and increasingly in Asia, especially China and Singapore. It is possible to envision more aggressive adoption if policies are implemented that require new buildings to engineer their roofs with live load allowances capable of holding soil and living plants.

1.3 Advantages and Disadvantages of Energy Efficient Roofs

1.3.1 Similar Solutions

For cool roofs and green roofs, major competing solutions include:

- Added roof insulation
- Ballasted roofs
- Cool walls and green walls
- Rooftop solar photovoltaics
- Rooftop solar thermal for hot water or space heating

Cool roofs represent a "no regret" improvement over conventional roofs: As detailed above, costs are equal or slightly higher and energy saving/GHG emissions reduction benefits are significant. In comparison with other competing solutions, cool roofs have important advantages:

- Applicability to every building type and size in ASHRAE climate zones 1-4; perhaps 1-5.
- Excellent life cycle economics, speicifically zero to low first cost increment.
- Consistent with existing roofing installation and maintenance expertise.

Green roofs, too, represent an alternative to conventional roofs that can reduce space cooling by reflecting sunlight, as cool roofs do, and reduce space heating loads by providing extra insulation. Though more costly and limited in application than cool roofs, green roofs provide unique additional benefits, including rainwater retention, unique aesthetics, enhanced biodiversity, and direct CO^2 removal.

Other solutions that compete with cool roofs and green roofs certainly have merit:

- Adding roof insulation, where feasible, is a simple and inexpensive way to reduce space cooling and heating loads and costs. Adding insulation thus *reduces* the thermal impact and economic value of a cool or green roof (roof insulation reduces the through-roof heat gain).
- A "ballasted roof is a conventional low-slope roof, usually a dark-colored membrane covered with light-colored stones that provide the 'ballast' to hold the membrane down and also reflect sunlight. It has been shown that ballasted roofs perform comparably with cool roofs" (Desjarlais 2008). ENERGY STAR, on its roofing website confirms: "The EPA recognizes that ballasted EPDM [a very durable synthetic rubber material] roofing systems are a very effective means of significantly lowering the roof top surface temperature similar to reflective roofing products." In this report ballasted roofs are treated as one type of cool roof.
- Cool walls represent an extension to vertical surfaces of the cool roof concept of reducing cooling loads via high solar reflectance. The energy savings calculations are more complex and site specific but, since the material used is essentially paint (vertical surfaces don't face the waterproofing requirement and wear-and-tear of a roof), the cost can be low. And since walls are usually less well insulated than roofs, the incremental impact can be high, with overall global impact of similar magnitude to that of cool roofs (Levinson et al 2018). In fact, the Cool Roof Rating Council in the US has been exploring an extension to cool walls (CRRC 2018).
- A rooftop solar system, whether photovoltaic or thermal, in addition to providing energy, also reflects and absorbs sunlight, thus reducing the rooftop heat gain and building space cooling load – and competing with cool or green roofs. Panels placed against the roof, or close to it, also perform a thermal insulation function, thus reducing the space heating load as well.

1.3.2 Arguments for Adoption

Cool Roofs

Cool roofs represent a "no regret" improvement over conventional roofs for reducing building energy consumption in ASHRAE climate zones 1-4; perhaps 1-5 (Levinson et al 2018, Pearson 2014). As detailed above, cool roof costs are equal or slightly higher and energy saving / GHG emissions reduction benefits are significant as compared with conventional roofs. So cool roofs can beneficially replace conventional roofs in most buildings at minimal incremental cost, thus reducing energy consumption and reducing CO_2 emissions.

Cool roofs have important advantages in comparison with other competing solutions:

- Applicability to every building type and size.
- Excellent life cycle economics, importantly including zero to low first cost increment.

- Consistent with existing roofing installation and maintenance expertise.

Cool Roofs also provide important ancillary benefits detailed below in "Additional Benefits and Burdens".

Green Roofs

In terms of climate impact, green roofs provide specific space cooling energy savings – and GHG reduction – similar to that of cool roofs. And like cool roofs, green roofs can help mitigate the urban heat island effect. In addition, unlike uninsulated cool roofs or conventional roofing, green roofs represent an added rooftop insulating layer that reduces space heating loads.

And though they have a substantial incremental first cost, green roofs can provide ancillary benefits unmatched by other building systems detailed below in "Additional Benefits and Burdens".

1.3.3 Additional Benefits and Burdens

Cool Roofs Additional Benefits and Burdens

Additional benefits resulting from extensive implementation of cool roofs, beyond reducing individual building space cooling energy needs, include:

- Reduced Urban Heat Island effect, i.e. reduced urban ambient temperatures, resulting in increased comfort and health benefits, especially in hot developing countries that lack space cooling (NRDC 2018).
- Reduced electric peak loads and correspondingly reduced investment in electricity infrastructure, especially generation and transmission.
- Reduced investment in building space cooling equipment (due to reduced cooling peak loads).
- Increased access to electricity in developing countries where capacity is already stretched (NRDC 2018).
- Extended roof lifetimes due to reduced operating temperatures.
- "Albedo effect" benefits, i.e., planet-wide temperature reduction due to increased solar reflectance (Akbari et al 2009).

Additional burdens are

- Increased space heating loads, costs, and GHG emissions in marginal locations (ASHRAE climate zones 4-5). Moisture condensation underneath the roof surface has been reported in some cooler regions (Urban & Roth, US DOE 2010).

- As a consequence of the space heating penalty, rewarding cool roofs within programs such as LEED, regardless of location (U.S. Green Building Council, 2015), may result in *less* energy efficient buildings in regions with high space heating requirements.
- Potential for glare and added heat gain (for better or worse) in nearby buildings.

Green Roofs Additional Benefits

In contrast to cool roofs, which represent an efficient manufactured functional engineering system narrowly designed for energy savings, green roofs have many "additional benefits" including:

- Helping to control storm water runoff during peak rainfall events, reducing sewer capacity requirements, and indirect emissions.
- Improving the aesthetic environment by providing an attractive, therapeutic, and valuable "amenity space", an urban "roof garden" for occupants to connect with nature, improving health, and increasing happiness and productivity.
- Retaining and enhancing local biodiversity and serving as a wildlife habitat.
- "Eco-affordability", making ecology accessible to low income urban residents.
- Sustainable rooftop urban agriculture to produce fresh local food.
- Air pollution mitigation.
- Increased roof lifespan due to reduced temperature fluctuation and exposure to sunlight, temperature fluctuations, and weather.

Each of these is discussed below.

Storm water mitigation. Controlling storm water runoff during peak rainfall events, has been one of the prime drivers of green roof mandates and incentives. Urban areas are characterized by pavement and other impervious surfaces that replace natural vegetated surfaces that absorb and slow rainwater, supplemented by engineered storm water systems to remove runoff. But these systems can be overloaded during rainstorms or snowmelt. Green roofs can provide a solution. Emulating natural vegetated systems, green roofs have the capacity to reduce water runoff by 65% and retain water for up to 3 hours, slowing its entry into the system. Further, they have the ability to permanently retain the first 1 to 2 cm of rain, preventing it from even entering into the system (Sproul 2014; GSA 2011). Table1.9 illustrates the impact this can have with an example from Southern California, a predominantly dry area with occasional heavy rains.

Table1.9. Green Roof Storm water Retention Illustration for Southern California

Scenario	Roof Area (million sq. meters)	Annual Rooftop Runoff Captured (billion liters)
High – Existing (50% Capture)	841.2	136.7
Low – Existing (35% Capture)	504.7	57.5
High – 2035 (50% Capture)	471.7	75.7
Low – 2035 (35% Capture)	283.0	31.8

Source: Garrison et al 2012; Drawdown analysis

Improving the aesthetic environment. It is well known that aesthetics improve human health and well-being. Renowned entomologist E.O Wilson coined the term "biophilia" and developed the biophilia hypothesis, which states that humans need and innately want to connect with nature (Kellert and Wilson 1993). Numerous studies since have supported this hypothesis and determined that living in areas devoid and absent of nature can have a deleterious effect on human health, and that interacting with and being surrounded by nature has positive impacts on human health and wellbeing (Grinde and Patil, 2009).

In the 1980s, Roger Ulrich conducted one of the first scientific studies on biophilia and human health. In his study, published in *Science*, he concluded that patient recovery time is reduced when views of nature are visible (Ulrich, 1984). Since his seminal study, the interchange between patient recovery time and biophilia has been significantly studied, with results showing significant improvement in patient health and wellbeing, i.e., reduced hospital stays, stress, and trauma. Now, entire hospital complexes are being designed with patient/nature interface in mind. The Khoo Teck Puat Hospital in Singapore is a prime example, whereby views of nature are accessible both inside and outside, rooftop gardens grow organic vegetables for patients, and there are private garden spaces where doctors can have sensitive health discussions with patients and families. At-risk patients such as geriatric and/or dementia patients also have closed garden areas where they can wander without fear of getting lost. Each of these biophilic design components adds to a beneficial patient experience, aids patient recovery, and reduces hospital operational costs.

In addition to providing an attractive and therapeutic biophilic environment, a green roof can provide food and the pleasure of gardening for urban dwellers. These urban gardens typically are intensive, requiring more than 15 cm of soil and maintenance due to the function of the garden. In an economic analysis for the city of Toronto, it was found that if all available rooftop space in the city was utilized to grow food stuffs (as well as other agricultural items such as nursery growth and biofuels), it could return a value of locally grown goods worth CAN$1.7billion (USD $1.4 billion[1]).

Retaining and enhancing biodiversity and habitat. Green roofs can provide increased habitat and biodiversity for local species, especially invertebrates. Incorporating specific types of plants can also deliberately attract specific species, such as pollinators – particularly helpful with a green roof vegetated garden. Whereas intensive and extensive roofs both support biodiversity, intensive roofs have been shown to become a habitat haven for some rare bird species (GSA, 2011).

Air pollution mitigation. Beyond sequestering carbon, plants are excellent at mitigating many forms of air pollution and even sequestering particulate matter (PM), through a process called "dry deposition" (removal due to gravity without involving precipitation). Green roofs can improve air quality around its immediate vicinity by removing PM and gasses such as nitrogen oxides, sulfur dioxides, carbon monoxide, carbon dioxide, and ground-level ozone; Berardi has conducted a good survey of this literature (Berardi 2014). And many studies have examined the impacts of green roofs on specific air pollutants: A 1997 German study for instance, demonstrated that green roof vegetation can significantly reduce diesel air pollution (Liesecke and Borgwardt 1997). Sulfur dioxide and nitrous acid were found to be 37% and 21% respectively lower directly above a newly installed green roof (Yok Tan and Sia, 2005). Other research has estimated that green roofs may be able to remove around 0.2 kg of dust particulates per year per square meter of grass roof (Peck and Kuhn 2001; Getter and Rowe 2006). Researchers also estimate that for every 1000 ft2 (93m2), a green roof can remove about 40lbs of PM per year (EPA, n.d.). Green roofs also reduce localized air pollution indirectly by reducing the UHI effect. With rising ground-level temperatures, ozone forms more easily. By integrating green roofs within an urban system, temperatures drop, further decreasing ozone creation and pollution and thereby raising air quality.

Increasing roof lifespan. As Table 1.5 indicates, typical roofs last for ~17 to 20 years. Green roofs, "because a green roof's vegetation layer and growing medium protect the roofing membrane from damaging UV radiation and from fluctuations in temperature extremes [that] cause daily expansion and contraction in the membrane, wearing it out over time", can last for 40 years or more (GSA 2011; Sproul 2014).

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[1] Conversion was done using OANDA Forex Trading site http://www.oanda.com/currency/converter/, accessed June 13, 2015 using the day's rates.

Green Roofs Additional Burdens

Green roofs also carry additional burdens. The largest, as discussed, is high construction and maintenance cost, especially if irrigation is needed. As complex living systems, green roofs draw on a range of interdisciplinary specialists, including structural, botanical, and other experts with specialized *local* knowledge and skills. For existing buildings, integration of a green roof can be complex and expensive, especially if structural changes are required – especially likely for heavy intensive designs. Risk of failure, especially leaks, is a concern and a driver of green roof high cost – especially in the absence of uniform materials standards and processes (Berardi et al 2014).

A technical consideration is the role of certain types of plants on green roofs in creating ozone. When assessing intensive roof vegetation, in particular, selection of plant species is key, especially when the building being retrofitted has poor ventilation and air quality. Some plants emit volatile organic compound (VOC) emissions, which are can lead to ground-level ozone creation (EPA, n.d.) and this should be considered for overall health and wellbeing of building occupants.

Energy Efficient Roof Solution Comparison

Table 1.10 compares cool roofs and green roofs with conventional roofs and a range of related energy-saving approaches in terms of aesthetics, breadth of application, GHG emissions reduction, fossil energy reduction, first cost, life cycle cost reduction, and comfort and health.

Compared with conventional roofs, cool roofs and green roofs both provide substantial GHG and fossil energy reduction. Cool roofs do so at zero or minimal increased first cost, with unchanged aesthetics and substantial life cycle cost reduction. Green roofs have higher first cost, and lower life cycle cost reduction, but higher aesthetics, and higher GHG emissions reduction (Green roofs actively consume CO^2).

Rooftop solar costs more than cool roofs, but in addition to providing shading, rooftop solar actively provides energy, reducing fossil energy and GHG emissions. External shading provides a benefit analogous to a cool roof at varied cost over a more limited breadth of application. High performance glass ranks high on aesthetics; performance varies greatly, depending on application details.

Table 1.10 Energy Efficient Roof Solution Comparison

Technology	Aesthetics	Breadth of Application	GHG Emissions Reduction	Fossil Energy Reduction	First Cost	Life Cycle Cost Reduction	Comfort and Health
Cool roof	Medium	High	Medium	Medium	Low	Medium-High	Medium-High
Green roof	High	Low	Medium-High	Medium	High	Low-Medium	High
Conventional roof	Medium	High	Low	Low	Low	Low	Low
Added roof insulation	N/A	Medium-High	Medium	Medium	Low	Medium-High	Medium
Rooftop solar photovoltaics	Low	Low-Medium	High	High	High	Medium	Medium-High
Rooftop solar thermal	Low	Medium	High	High	High	Medium	Medium-High
External shading	Varies	Medium	Low-Medium	Low-Medium	Low-Medium	Low-Medium	Medium
High performance glass for roofs and windows	High	High	Varies	Varies	Medium-High	Low-Medium	Medium-High

Source: Drawdown Analysis

Table 1.11 Ratings Key for Efficient Roof Solution Comparison

Level	Aesthetics	Breadth of Application	GHG Emissions Reduction	Fossil Energy Reduction	First Cost	Life Cycle Cost Reduction	Comfort and Health
High	67% to 100% of solutions	67% to 100% of buildings	67% to 100% of solutions	67% to 100% of solutions	Top 1/3	Top 1/3	Top 1/3
Medium	33% to 66% of solutions	33% to 66% of buildings	33% to 66% of solutions	33% to 66% of solutions	Middle 1/3	Middle 1/3	Middle 1/3
Low	0% to 33% of solutions	0% to 33% of buildings	0% to 33% of solutions	0% to 33% of solutions	Bottom 1/3	Bottom 1/3	Bottom 1/3

2 METHODOLOGY

2.1 INTRODUCTION

Project Drawdown's models are developed in Microsoft Excel using standard templates that allow easier integration since integration is critical to the bottom-up approach used. The template used for this solution was the Reduction and Replacement Solutions (RRS) Model which accounts for reductions in energy consumption and emissions generation for a solution relative to a conventional technology. These technologies are assumed to compete in markets to supply the final functional demand which is exogenous to the model, but may be shared across several solution models. The adoption and markets are therefore defined in terms of functional units, and for investment costing, adoptions are also converted to implementation units. The adoptions of both conventional and solution were projected for each of several scenarios from 2015 to 2060 (from a base year of 2014) and the comparison of these scenarios (for the 2020-2050 segment) is what constituted the results.

This Technical Assessment models each energy-efficient roof Solution, Cool Roofs and Green Roofs, separately in comparison with conventional roofing. Both models use the same functional unit – one square meter of roof area, which also doubles as the implementation unit. To model each solution, a separate 2014 total addressable market (TAM) is estimated for each type of roof, and then projected from 2014 to 2060 based on Drawdown total residential and commercial roof area forecasts and "filters" addressing limitations in applicability of each efficient-roof Solution. These filters are derived from a literature review of the applicability of each rooftop Solution. For example, Green Roofs cannot be installed on many existing buildings which cannot sustain the additional weight; Cool Roofs are unsuited for some historical tile-roof buildings that cannot be altered for aesthetic reasons. The filter details are presented below in the Cool Roof and Green Roof Total Addressable Markets section.

Financial variables are statistically assessed by comparing multiple sources of first cost, including cost of acquisition and implementation of the solution, and operating cost. Operating cost includes standard roof operations and maintenance, as well as roof-related energy costs, such as the "space heating penalty" for Cool Roofs. The Green Roof model includes one unique operating cost – stormwater management. Many cities charge an annual fee for buildings with conventional "hard surface" roofs that don't retain stormwater, and some cities provide incentives for Green Roofs that do. The Green Roof model treats stormwater management as an added operating cost for conventional roofs and a "zero cost" for Green Roofs.

Roofing first cost data is usually stated per unit area ($\$US/m^2$) in the literature, but sometimes is presented as a total project cost for a specific building ($US). Operating cost data is often stated as a cost per unit area per year ($\$US/m^2$-year), but sometimes as a fractional increase or reduction in comparison with conventional roofing operating cost (%). Conventional roofing costs are not always disclosed in accordance with the reported increase or reduction, so in those cases a conventional operating cost is calculated, and then the data reporting an increase or reduction applied to that calculated conventional operating cost value.

A similar methodology is used for the climate variables where the literature reports values as a reduction without always indicating the conventional energy or emissions load.

Energy modeling of Cool Roofs and Green Roofs examines their two primary impacts on building energy use, and hence on GHG emissions: Reduction of space cooling energy and reduction, in some cases an increase, in space heating energy. For space cooling, each model compares the electricity consumed by a building with conventional roofing with the electricity consumed by a Cool Roof- or Green Roof-covered building (kWh/m^2-year).

For space heating, each model inputs the fuel consumed by a conventionally-roofed building (TJ/m^2-year) and the *fractional change* of fuel consumption due to the Cool Roof or Green roof (%) (not the reduction in space conditioning energy as is done with other models). This causes a technical complication in modeling, since in the literature this change in fuel consumption is usually stated as a fraction of top floor or single-story fuel consumption, necessitating an extrapolation across buildings of all numbers of stories. Cool Roofs usually *increase* building fuel consumption, the “space heating penalty”, because Cool Roofs reflect sunlight in winter and reduce solar heat gain. Green Roofs usually *reduce* fuel consumption due to the insulating effect of Green Roofs.

As one important refinement, both models *weight* space heating and space cooling energy consumption by climate zone using the filters detailed in Table 2.2 in Total Addressable Market below. Each model, as it calculates and statistically assesses space cooling and space heating loads for a conventional roof in comparison with the energy-efficient roof, uses these filters to weight data from various regions in order to calculate net energy savings, energy cost savings, and GHG emissions impacts. Weighting has two impacts:

- It helps to more accurately calculate the global impact of each efficient-roof Solution, i.e., modeling each Solution where it can have positive impact – and hence would actually be applied in practice – and not “penalizing” the efficient-roof Solutions by modeling them in locations where they are not suited and would not be used.

- By limiting each Solution to certain Climate Zones and types of buildings, filtering reduces the TAM accessible to each efficient-roof Solution.

2.2 Data Sources

Table 2.1 summarizes some of the most important data sources incorporated in this Technical Report:

Table 2.1 Key data sources

Input Data	Key Data Sources
Rooftop Total Addressable Market	• Drawdown analysis based on IEA 2013 and GBPN 2012
Current and Future Adoption	• **Cool Roofs:** Drawdown analysis based on CBECS / US DOE 2016, Shickman 2019, EPA 2008, Transparency Research 2019 • **Green Roofs**: Drawdown analysis based on greenroofs.com 2019, Velazquez 2019, Green Roofs for Healthy Cities 2017, US DOE 2012, Castleton et al 2010, EFB 2015
Financial	• **Cool Roofs:** Sproul et al 2014, Means 2012, Levinson et al 2010, Gao et al 2014, Ascione et al 2013, Moseley et al 2013, US GSA 2011 • **Green Roofs**: US GSA 2011, Garrison et al 2012, Sproul et al 2014, Peck & Kuhn 2010, Bianchini & Hewage 2012
Energy Consumption	• Ascione et al 2013, Gao et al 2014, Jaffal et al 2012, Levinson et al 2010

Section 2.3 describes Drawdown's analytical approach for calculating total addressable market. Section 2.4 presents Drawdown's approach for developing energy-efficient roof adoption scenarios.

2.3 Cool Roof and Green Roof Total Addressable Markets

The Cool Roof and Green Roof TAMs modeled are each based on two foundations:

- Drawdown development of global rooftop TAM (and building height estimates).
- Filters developed to select climate zones and building types suited for each efficient roof technology.

Global Rooftop Total Available Market Methodology

An integrated Total Addressable Market (TAM) for total roof area was created alongside other TAMs used by different Drawdown Solutions. This integrated TAM is developed using population and GDP as the primary driver for residential and commercial floor space demand, respectively. Present day and historical floor area estimates were derived from two primary data sources, the International Energy Agency (IEA) and Global Buildings Performance Network (GBPN) which were then projected from 2014 to 2060 using the medium UN variant for population and expected GDP growth as to be integrated with all Drawdown Solutions.

Utilizing the following relationship between floor area and roof area, the roof area TAM is then created:

$$Roof\ Area[million\ m^2] = \frac{Floor\ Area[million\ m^2]}{Number\ of\ stories\ [-]}$$

The number of stories for buildings is estimated through a meta-analysis performed by the US Geological Survey (USGS) of global seismic hazards (Jaiswal and Wald, 2008), which examined 67 building typologies (both residential and commercial). Using regional expert judgement, the pervasiveness of each typology was determined and weighted for each country of the world. These weighted averages for number of stories per building (1.577 for commercial and 1.576 for residential) were used in the Drawdown analysis to create the roof area TAM.

Cool Roof and Green Roof TAM Filters

The input for energy-efficient roof modeling from the Drawdown TAM analysis is total global roof area (m^2) for residential and commercial buildings for each year from 2012 to 2060. These TAMs were apportioned into ASHRAE climate zones based on 2015 population share for residential buildings, and 2015 GDP share for commercial buildings. These allocations were applied for every year from 2012 to 2060.

Next, three multiplicative filters were applied to circumscribe the TAMs for Cool Roofs and Green Roofs to those locations and building types where each rooftop technology would be well-suited.

- ASHRAE Climate Zones (CZ) (Hermans et al 2006)
- Building application: "Current Building" as of 2014, or "New Building" if constructed after 2014.
- *Overlap* filter to constrain the sum of the Cool Roof and Green Roof TAMS to never exceed total global roof area TAM. This filter reduced global efficient roof TAMS from 0% through 2026 to as much as 5% by the late 2050s.

Table 2.2 presents the Climate Zone and Building Type filters applied to calculate Cool Roof and Green Roof TAMs.

Table 2.2 Energy-Efficient Roof Climate Zone and Building Filters

Climate Zone	Cool Roofs	Green Roofs
0	100%	50%
1	100%	50%
2	100%	50%
3	100%	100%
4	100%	100%
5	0%	100%
6	0%	100%
7	0%	0%
8	0%	0%
Building Types	**Cool Roofs**	**Green Roofs**
Current Buildings (2014 and Before)	80%	15%
New Buildings (Post 2014)	90%	50%

As Table 2.2 indicates, Cool Roofs, which help reduce cooling loads, are especially well suited for hot regions, Climate Zones 1-3. There is some debate as to the viability of Cool Roofs in CZs 4-5, due to the space heating penalty, and Cool Roofs are usually viewed as not desirable for most buildings in very cold CZs 6-8 (Levinson et al, 2018; Levinson et al 2010). In terms of building application, economical Cool Roof products are available for reroofing almost all flat-roofed buildings or shingled steep-roofed buildings. Existing tile roofs can be coated or replaced with Cool Roof tiles. And a Cool Roof solution exists for almost all new buildings (CRRC Product Database).

Green Roofs are suited for locations where vegetation will grow without irrigation – CZs 3-6 and the humid portions of very hot CZs 0-2. Green Roofs are not suited for extremely cold regions, such as CZs 7-8 or for hot arid regions (portions of CZs 0-2) unless irrigated. It is estimated that Green Roofs can be applied to 15% of existing buildings and 50% of new buildings, based on very limited data (Castelton 2010; Peck 2019; Berardi 2014).

Table 2.3 summarizes the Drawdown TAM estimates for total global rooftop area, Cool Roof area, and Green Roof area.

Table 2.3 TAM Estimates for Cool Roofs and Green Roofs

Year	Total Rooftop TAM ($10^9 m^2$)	Cool Roof TAM ($10^9 m^2$)	Green Roof TAM ($10^9 m^2$)
2014	131.6	89.2	13.9
2050	222.5	145.0	45.6

2.4 Cool Roof and Green Roof Adoption Scenarios

Two different types of adoption scenarios were developed: a Reference (REF) Case which was considered the baseline, where very little changes in the world, and a set of Project Drawdown Scenarios (PDS) with varying levels of ambitious adoption of the solution. Published results show the comparison of one PDS to the REF, and therefore focus on the change to the world relative to a baseline.

The starting point for all adoption scenarios is 2018 adoption, as detailed in Current Adoption (2014-2018 adoptions are based on estimates of historical adoptions and are constant for all scenarios):

- Cool Roof current adoption: 5.36% of 2018 Cool Roof TAM, or 5.07 billion m^2
- Green Roof current adoption: 1.16% of 2018 Green Roof TAM, or 198 million m^2

2.4.1 Reference Case / Current Adoption

The Reference case assumes that the 2018 ratios of Cool Roof or Green Roof adoption / TAM remain constant from 2018 to 2060. No major shifts in technologies or policies occur; conventional roofs continue to dominate the market.

2.4.2 Project Drawdown Scenarios

Three Project Drawdown Scenarios (PDS) were developed for each Solution, to compare the impact of an increased adoption of the solution to a reference case scenario. Scenario descriptions and 2014 and 2050 adoption levels are presented in Table 2.4:

Table 2.4 Summary of Project Drawdown Cool Roof & Green Roof Adoption Scenarios

Variable Description	Roof Type	Variable Year	Reference Scenario	Plausible Scenario	Drawdown Scenario	Optimum Scenario
			Reference / Baseline	Realistically vigorous adoption	Optimized to achieve drawdown by 2050	98% of “Adjusted TAM”* by 2050

Variable Description	Roof Type	Variable Year	Reference Scenario	Plausible Scenario	Drawdown Scenario	Optimum Scenario
Adoption Growth: S-Curve Based On:			Constant share of roof area	7% CAGR from 2018-2050 consistent with reported growth	9% CAGR from 2018-2050	~100% of Adjusted TAM in 2050
Adjusted TAM ($10^9 m^2$)	Cool	2014	89.2	89.2	89.2	89.2
Share of TAM (%)	Cool	2014	2.29%	2.29%	2.29%	2.29%
Adjusted TAM ($10^9 m^2$)	Cool	2018	94.7	94.7	94.7	94.7
Share of TAM (%)	Cool	2018	5.36%	5.36%	5.36%	5.36%
Adjusted TAM ($10^9 m^2$)	Cool	2050	145.0	145.0	145.0	145.0
Share of Roof TAM (%)	Cool	2050	5.36%	30%	47.8%	98%
Adjusted TAM ($10^9 m^2$)	Green	2014	13.8	13.8	13.8	13.8
Share of Roof TAM (%)	Green	2014	1.08%	1.08%	1.08%	1.08%
Adjusted TAM ($10^9 m^2$)	Green	2018	17.1	17.1	17.1	17.1
Share of Roof TAM (%)	Green	2018	1.16%	1.16%	1.16%	1.16%
Adjusted TAM ($10^9 m^2$)	Green	2050	45.6	45.6	45.6	45.6
Share of Roof TAM (%)	Green	2050	1.16%	9%	13%	99%

***Adjusted TAM = Roofs & climate zones where Cool Roofs & Green Roofs are feasible and save energy**

Each Cool Roof or Green Roof PDS adoption scenario is based on a logistic S-curve that starts from 2018 current adoption and corresponds approximately with a 2018-2050 growth rate set to match the scenario description.

Plausible Scenarios

The Plausible Scenarios represent "realistically vigorous adoption". For both Cool Roofs and Green Roofs 2050 S-curve adoption was set to correspond with a 7% 2018-2050 CAGR – approximately the growth forecast in each market for 2014 to ~2025, and pretty high growth for the slowly-growing building industry. As Table 2.4 details, this results in Cool Roof adoption of 30% of the 145 billion m^2 2050 Cool Roof TAM and Green Roof adoption of 9% of the 45.6 billion m^2 2050 Green Roof TAM.

Drawdown Scenario

The Drawdown Scenarios are "optimized to achieve drawdown by 2050." For a single product, such as Cool Roofs or Green Roofs, this is difficult to quantify in isolation. So, for both Cool Roofs and Green Roofs, 2050 S-curve adoption was set to correspond with a 9% 2018-2050 CAGR. As Table 2.4 details, this results in Cool Roof adoption of 47.8% of the 145 billion m^2 2050 Cool Roof TAM – almost half the TAM – and Green Roof adoption of 13% of the 45.6 billion m^2 2050 Green Roof TAM.

Optimum Scenario

The Optimum Scenarios are geared to "achieve maximum potential, fully replacing conventional technologies" by 2050. This corresponds with energy-efficient roofs achieving 100% of "adjusted TAM" – the TAM obtained by filtering total rooftop TAM by those climate zones and building types where each efficient-roof technology is suited. Achieving Cool Roof adoption of close to 100% of the 145 billion m^2 2050 Cool Roof TAM equates approximately with a 2018-2050 growth rate of 11%. Green Roof adoption of ~100% of the 45.6 billion m^2 2050 Green Roof TAM corresponds with a growth rate of ~17%.

2.5 INPUTS

2.5.1 Climate Inputs

The climate analysis in this model uses the values for energy intensity of space heating and reductions in energy consumption from heat pump usage (which are general "Technical" inputs in the Technical Inputs section). To calculate key model results, reported emissions factors for both electricity and fuel are used. Emission factors for electricity generation are derived from the projected energy generation mix from three AMPERE RefPol scenarios in IPCC AR5 model Database (GEM3, IMAGE, MESSAGE) and the IEA's ETP 6DS scenario, and direct/indirect emissions factors by generation type taken from the IPCC AR5 Model Database, AMPERE3-MESSAGE Base scenario. The reader should note that since this combined reference projection includes a shift away from coal and oil to natural gas, the reference emissions factors decline slowly over the analysis period. Fuel emission factors are calculated using the methodology recommended in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2, Annex 1. The values used are shown in Table 2.5.

To calculate the climate impacts of energy efficient roof adoption in the PDS scenarios, estimations were made of the total reduction in both electricity and fuel consumption for space heating per TWh of space heating demanded. Emissions factors for grid electricity and fuel are applied to calculate maximum annual emissions reduction, total emissions reduction, and concentration change (in PPM equivalent). Then emissions reductions are calculated by applying the following equation for each year:

$$CO_2reduced = (Reduction\theta_{PDS}) \cdot (G_{ef}) + \sum_{each\ fuel} (Reduction\delta_{PDS}) \cdot (\mathrm{F}_{ef})$$

where:

- $CO_2reduced$ is the CO_2-eq emissions reduction associated with the reduction in energy consumption in each PDS scenario.
- $Reduction\theta_{PDS}$ is the reduction in energy consumption (TWh).
- G_{ef} is the emissions factor (in $t$$CO_2$-eq / TWh) of grid electricity globally for each year.
- $Reduction\delta_{PDS}$ is the reduction in fuel consumption (TJ) for space heating in each PDS scenario for each fuel.
- F_{ef} is the fuel emissions factor (in $t$$CO_2$-eq / TJ) for each fuel.

Updating of Grid Emissions Factors

As electricity sector Drawdown solutions are adopted, the grid will become cleaner, and the high emissions factor shown in Table 2.5 will decline. This is not calculated directly in the model as is considered an integration issue. This is dealt with in the Integration section of this report.

Table 2.5 Climate Inputs

Variable	Unit	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Global average REF Grid Emissions Factor	g CO_2e/ kWh	503-593	Depends on year. Starts at High Input in 2020 declines to Low Input in 2050	12 each year	4
Combined REF Space Heating & Cooling Fuel Emissions Factor	t CO_2e/ TJ of fuel	N/A	87	8 including individual fuel emissions factors and shares	1

Sources: IEA (2016) ETP, AMPERE Public Database (Version 1.0.0) https://secure.iiasa.ac.at/web-apps/ene/AMPEREDB for Models: GEM-E3, IMAGE and MESSAGE

2.5.2 Financial Inputs

Table 2.6 presents the financial inputs for conventional roofs, Cool Roofs, and Green Roofs. Key sources for these data are presented in Table 2.1. A few key financial highlights:

- Conventional and Cool Roof first costs (material plus installation) are very similar at ~$23/m^2; Green Roof first cost is much higher at ~$200/m^2.
- Lifetimes of conventional and Cool Roofs are similar at about 18 years; Green Roofs can last 38 years or more.
- Fixed operating costs are also similar for conventional and Cool Roofs at around $0.5/m^2-year; Green Roof O&M averages $3.2/m^2-year; this can vary widely depending on the "intensity" of the roof.
- Variable operating cost is a combination of cooling energy reductions for Cool and Green Roofs, heating energy penalty for Cool Roofs, and (in the Green Roof model) stormwater management costs for Conventional Roofs.

Table 2.6 Financial Inputs for Conventional, Cool, and Green Roofs

Variable	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Installation Cost/ First Cost: Conventional	US$2014/$m^2$	21.12-25.50	23.31	3	3
Installation Cost/ First Cost: Cool Roof	US$2014/$m^2$	21.71-29.01	25.36	9	6
Installation Cost/ First Cost: Green Roof	US$2014/$m^2$	125.29-265.50	195.40	20	12
Fuel Cost: Conventional	US$2014/$m^2$/yr	N/A: Calculated from fuel use	1.32	N/A	N/A
Fuel Cost: Cool Roof	US$2014/$m^2$/yr	N/A	Not used	N/A	N/A
Fuel Cost: Green Roof	US$2014/$m^2$/yr	N/A	Not used	N/A	N/A
Lifetime: Conventional	Years	17-20	18.5	2	2
Lifetime: Cool Roof	Years	17-20	18.5	2	2
Lifetime: Green Roof	Years	35.98-40.69	38.33	3	3
Variable Operating Cost: Conventional (Green Roof model)	US$2014/$m^2$/yr	0.40-11.41	2.40	5	4
Variable Operating Cost: Cool Roof *Net Reduction vs. Conventional* due to cooling energy reduction minus heating penalty	US$2014/$m^2$/yr	-0.295 to +1.597	0.651	15	4
Variable Operating Cost: Green Roof (composite calculation from O&M minus energy cost savings)	US$2014/$m^2$/yr	-2.37 to +8.59	3.11	3-10	4-6
Fixed Operating Cost: Conventional	US$2014/$m^2$/yr	0.200-0.678	0.439	2	2
Fixed Operating Cost: Cool Roof	US$2014/$m^2$/yr	0.291-0.873	0.582	3	3
Fixed Operating Cost: Green Roof (O&M only)	US$2014/$m^2$/yr	-1.28 to +7.68	3.20	7	7
Discount Rate for Future Cash flows	Percent	3.0-10.3	4.5	12	9

2.5.3 Technical Inputs

Besides climate and financial inputs, some variables, termed Technical Inputs, have been defined which apply to both climate and financial results. Because modeling is conducted with weighted data, some of the weighted technical inputs differ between the Cool Roof and Green Roof models. Table 2.7 presents the technical inputs for the Cool Roof model, using the Climate Zone weighting and filters suited for Cool Roofs. As Table 2.7 indicates, Cool Roofs reduce space cooling electricity by about 9% on average. Cool roofs also *increase* heating fuel consumption about 9%, so cool roofs are most suited for locations where the heating loads are low so that the space heating *energy* penalty is small.

Table 2.7 Technical Inputs for Conventional and Cool Roofs: Cool Roof Model

Variable	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Space Heating and Cooling Electricity Consumed: Conventional Roof	kWh/(m^2 Roof Area-Year)	28.4-80.3	54.4	17	3
Space Heating and Cooling Electricity Consumed: Cool Roof	kWh/(m^2 Roof Area-Year)	36.1-62.3	49.2	15	3
Fuel Consumed: Conventional Roof	MJ/(m^2 Roof Area-Year)	0.0-240	66.5	17	3
Fuel *Penalty*: Cool Roof	Percent of Conventional-Roofed Building Fuel	2.70%-15.74%	9.22%	15	3
Global Average Number of Floors: Commercial Buildings	Floors	N/A: Drawdown analysis	1.577	N/A	N/A
Global Average Number of Floors: Residential Buildings	Floors	N/A: Drawdown analysis	1.576	N/A	N/A
Global Average Number of Floors: All Buildings	Floors	N/A: Drawdown analysis	1.576	N/A	N/A

Table 2.8 presents the technical inputs for the Green Roof model, using the Climate Zone weighting and filters suited for Green Roofs. Key takeaways: In the cooler climate zones that Green Roofs target, conventional roof space cooling electricity consumption is slightly lower and heating fuel consumption is much higher than in the Cool Roof model summarized in Table 2.7. Additionally, unlike Cool Roofs, Green Roofs *reduce* space heating fuel consumption due to their insulating value. The *fractional* energy savings are comparable (~7% to 9%), but the specific space heating energy impact (TJ/m^2) of Green Roofs is much higher, since heating loads are much higher in these cooler climate zones.

Table 2.8 Technical Inputs for Conventional and Green Roofs: Green Roof Model

Variable	Units	Project Drawdown Data Set Range	Model Input	Data Points (#)	Sources (#)
Space Heating and Cooling Electricity Consumed: Conventional Roof	kWh/(m^2 Roof Area-Year)	16.0-70.4	43.2	9	2
Space Heating and Cooling Electricity Consumed: Green Roof	kWh/(m^2 Roof Area-Year)	13.4-69.8	41.6	9	2
Fuel Consumed: Conventional Roof	MJ/(m^2 Roof Area-Year)	0.0-530	263	17	3
Fuel Saved: Green Roof	Percent of Conventional-Roofed Building Fuel	0.00%-12.85%	6.86%	6	1
Global Average Number of Floors: Commercial Buildings	Floors	N/A: Drawdown analysis	1.577	N/A	N/A
Global Average Number of Floors: Residential Buildings	Floors	N/A: Drawdown analysis	1.576	N/A	N/A
Global Average Number of Floors: All Buildings	Floors	N/A: Drawdown analysis	1.576	N/A	N/A

2.6 Assumptions

Six overarching assumptions have been made for Project Drawdown models to enable the development and integration of individual model solutions. These are that the infrastructure required for a solution is available and in-place; necessary policies are already in-place; no carbon price is modeled; all costs accrue at the level of agency modeled; improvements in technology are not modeled; and that first costs may change according to learning. Full details of core assumptions and methodology will be available at www.drawdown.org. Beyond these core assumptions, there are other important assumptions made for the modeling of this specific solution. These are detailed below.

Assumption 1: The cost of implementing Cool Roofs and Green Roofs is consistent across all regions and at all scales. In reality, unit costs are lower for larger systems, especially for Green Roofs. Cost savings per square meter of Green Roof installation assumes an extensive roof type – the most basic type of green roof, with little substrate needed to host the roof. This is because intensive Green Roof costs can be dramatically higher than the more utilitarian extensive roofs, and because little data exists to quantify energy savings differences between extensive and intensive Green Roofs.

Assumption 2: No weighted averages were needed for any financial or climate variables (due to lack of regional data, especially for cool roofs). This study weights regional climate data only in assessing electricity and fuel consumption inputs. It's implicit that a green roof in Singapore would have different energy savings than would, say, a green roof in Russia.

Assumption 3: Cool roof heating energy penalties can be assessed on a climate zone weighted basis, since the TAM is weighted to regions that should limit potential for such a penalty.

Assumption 4: Green roof space heating energy reductions are assessed as a fuel emissions reduction in the model by applying a global weighted average emissions factor.

Assumption 5: Cool Roofs reduce cooling which is assumed to be electricity, while Cool Roof heating energy use penalty is assessed as a negative efficiency for fuel emissions related to space heating and cooling.

Assumption 6: Direct impacts of increased albedo effect on entire atmosphere are not critical to results (lack of confirmed and measured impact).

Assumption 7: No learning rate is assumed for either solution (green roofs may indeed show some decrease in first costs over time, but such reductions are discounted in this model).

2.7 INTEGRATION

The complete Project Drawdown integration documentation (available at www.drawdown.org) details how all solution models in each sector are integrated, and how sectors are integrated to form a complete system. Those general notes are excluded from this document but should be referenced for a complete understanding of the integration process. Only key elements of the integration process that are needed to understand how this solution fits into the entire system are described here.

Each solution in the Buildings Sector was modeled individually, and then integration was performed to ensure consistency across the sector and with the other sectors. These solutions require an integration analysis to avoid double counting, as they primarily relate to either reducing demand for space heating and cooling (for residential and/or commercial buildings), commercial lighting, cooking, or water heating. The integration process therefore was addressed through sequential adjustments to the efficiencies of the solutions in a prioritized sequence for each of space heating and cooling, lighting, cooking, and water heating (performed in four separate sequence chains). The prioritized sequence is fixed for all scenarios and is described in the Drawdown Building Sector Integration documentation.

For each solution in an integration sequence, the estimated impact of previous solutions on the emissions savings of the current solution is estimated and a reduction factor is applied. The factor is only applied to emissions and energy savings attributed to adoptions that overlap with previous solutions[2], and for this adoptions are generally assumed independent. Solutions that start each integration sequence are therefore unaffected (unless they are affected by solutions in other sequences), and solutions that apply to different buildings (say commercial and residential) do not affect each other. The method of estimating overlap is based on the percent adoption of the higher priority solution applied to the area adopted in the lower priority solution. For the efficiency factor of this overlapping area only, the reduction factor is applied; it is scaled and used to update the results in the lower priority solution model.

The Cool Roofs and Green Roofs solution (of the space heating and cooling sequence) is assumed to interact with only higher priority solutions that are modeled; in this case, Insulation. Insulation, however, is only modeled on Residential buildings, so only this segment is integrated for Cool Roofs and Green Roofs. The Residential Roof area components of the Cool and Green Roof adoptions were estimated assuming the ratio between Residential and Commercial Roof area adoption is the same as the ratio of the Residential and Commercial TAM Roof area in each year. The share of the Cool Roof and Green (residential) roof area that overlaps with Insulation is then estimated by taking the fraction of the total residential TAM that is adopted with insulation each year and multiplying it by the Residential Roof Area adopted for Cool and Green Roofs. The total overlap ranges between 50% and 58% of the total Commercial and Residential Roof area (depending on scenario).

A reduction factor is applied to the energy savings and energy penalties for only this overlapping area. Without good data, an assumption of a 50% impact reduction factor was used, and this was scaled to all adoption to estimate the Electricity and Fuel consumption for Cool Roofs and Green Roofs taking into

[2] This can be interpreted as a single building with multiple efficiency technologies.

account the reductive impacts of Insulation on Residential Buildings. Results in this report reflect the results of the modeling and integration process.

In addition to building sector integration, there was an integration process across the grid and electricity efficiency solutions (buildings, transport, materials etc.) which adjusted for double counting. Double counting of emissions reduction was a factor of using the reference grid emissions factors for electricity-based solutions. As grid solutions (Utility-scale Solar PV and others) are adopted, the grid gets cleaner and the impact of efficiency solutions is reduced (where they reduce electricity demand) or increased (where they increase electricity demand[3]). Grid solutions are adjusted to remove the double counting as described in the Project Drawdown integration documentation.

2.8 Limitations/Further Development

Modeling of energy efficient roofs faces two key limitations:

- Little data is available to quantify market adoption and future market forecasts. This is a major barrier for Cool Roofs outside the USA, and for Green Roofs (outside of Germany) for which most data that is available is anecdotal and local, or at best regional. This necessitates multiple estimations and approximations to carry out the modeling.
- Both models currently use climate zone weighting for a few energy variables. It would be valuable to perform energy *difference* calculations at the climate zone level, before rolling these up to the global result. Within fuel modeling (space heating) energy differences can only be modeled as a fractional reduction or increase in comparison with conventional energy consumption. It would be an improvement to model fuel usage as a difference (as electricity consumption can now be modeled) and to do so at the climate zone level before rolling up for the global result.

[3] Some solutions, such as Electric Vehicles and High-Speed Rail, increase the demand for electricity and reduce the demand for fuel.

3 Results

3.1 Adoption

Table 3.1 presents the world adoptions of Cool Roofs and Green Roofs in functional units and percent for the three Project Drawdown scenarios.

Figure 3.1 and Figure 3.2 graphically display these outputs through 2060.

Table 3.1 World Adoption of Cool Roofs and Green Roofs

Solution	Units	Current Year (2018)	World Adoption by 2050		
			Plausible	Drawdown	Optimum
Cool Roofs	*10^9 m2 Rooftop Area*	5.1	43.8	69.4	142.3
	(%Adjusted Rooftop TAM – Cool Roofs Only)	5.4	30.2	47.9	98.1
Green Roofs	*10^9 m2 Rooftop Area*	0.20	4.0	5.8	45.0
	(% Adjusted Rooftop TAM – Green Roofs Only)	1.2	8.8	12.6	98.6

Figure 3.1 Cool Roof World Annual Adoption 2020-2050

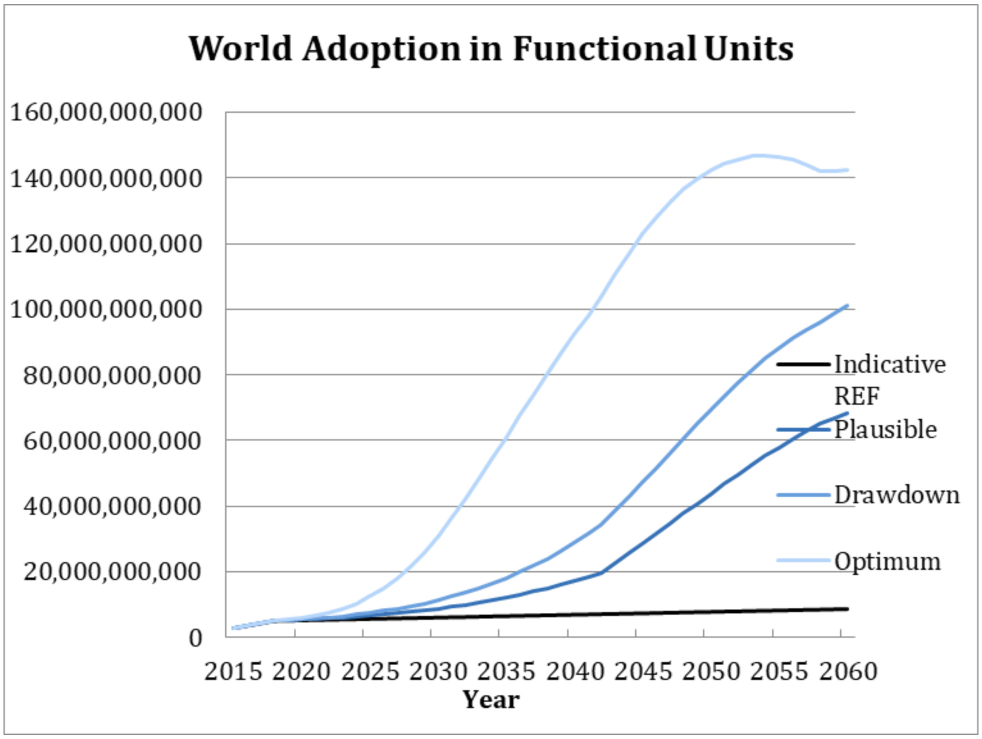
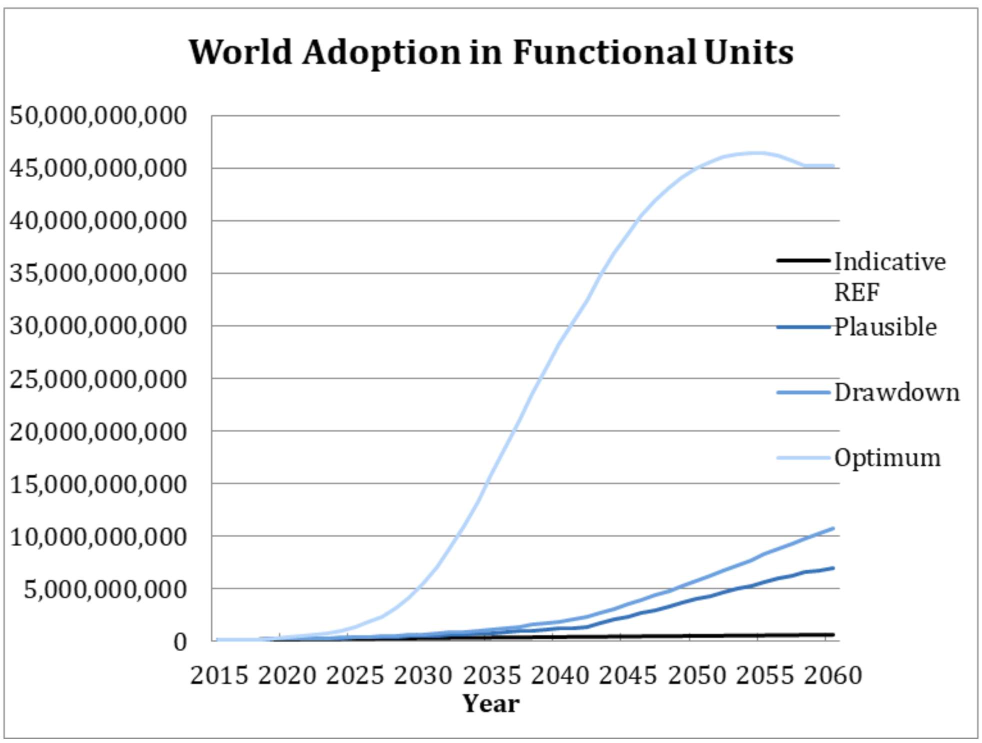


Figure 3.2 Green Roof World Annual Adoption 2020-2050



3.2 CLIMATE IMPACTS

Below are the emissions results of the analysis for each scenario which include total emissions reduction, atmospheric concentration changes, and sequestration where relevant. For a detailed explanation of each result, please see the Glossary (Section 6).

Table 3.2 Cool Roof Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
Plausible	0.07	0.66	0.01	0.07
Drawdown	0.13	1.25	0.01	0.13
Optimum	0.28	4.01	0.06	0.28

Table 3.3 Green Roof Climate Impacts

Scenario	Maximum Annual Emissions Reduction	Total Emissions Reduction	Emissions Reduction in 2030	Emissions Reduction in 2050
	(Gt CO_2-eq/yr.)	*Gt CO_2-eq/yr. (2020-2050)*	(Gt CO_2-eq/year)	*(Gt CO_2-eq/year)*
Plausible	0.01	0.06	0.00	0.01
Drawdown	0.01	0.10	0.001	0.01
Optimum	0.11	1.31	0.011	0.11

The solution was integrated with all other Project Drawdown solutions and may have different emissions results from the models. This is due to adjustments caused by interactions among solutions that limit full adoption (such as by feedstock or demand limits) or that limit the full benefit of some solutions (such as reduced individual solution impact when technologies are combined).

Table 3.4 Cool Roof Impacts on Atmospheric Concentrations of CO_2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible	0.06	0.007
Drawdown	0.11	0.011
Optimum	0.35	0.022

Table 3.5 Green Roof Impacts on Atmospheric Concentrations of CO_2-eq

Scenario	GHG Concentration Change in 2050	GHG Concentration Rate of Change in 2050
	PPM CO_2-eq (2050)	*PPM CO_2-eq change from 2049-2050*
Plausible	0.01	0.001
Drawdown	0.01	0.001
Optimum	0.12	0.009

Figure 3.3 Cool Roof World Annual Greenhouse Gas Emissions Reduction

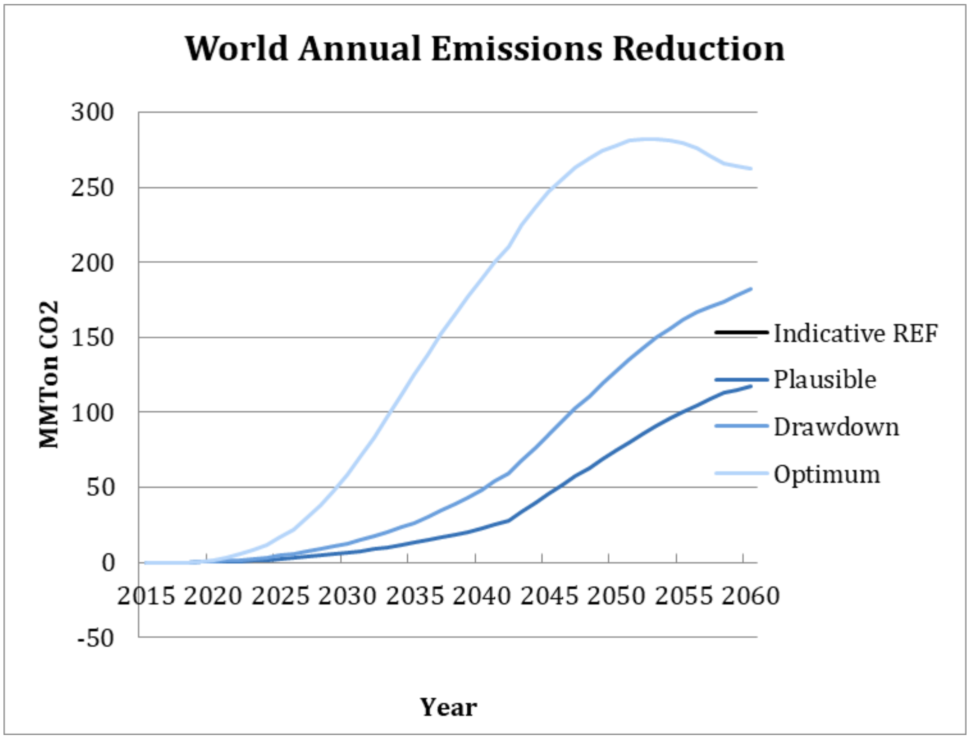
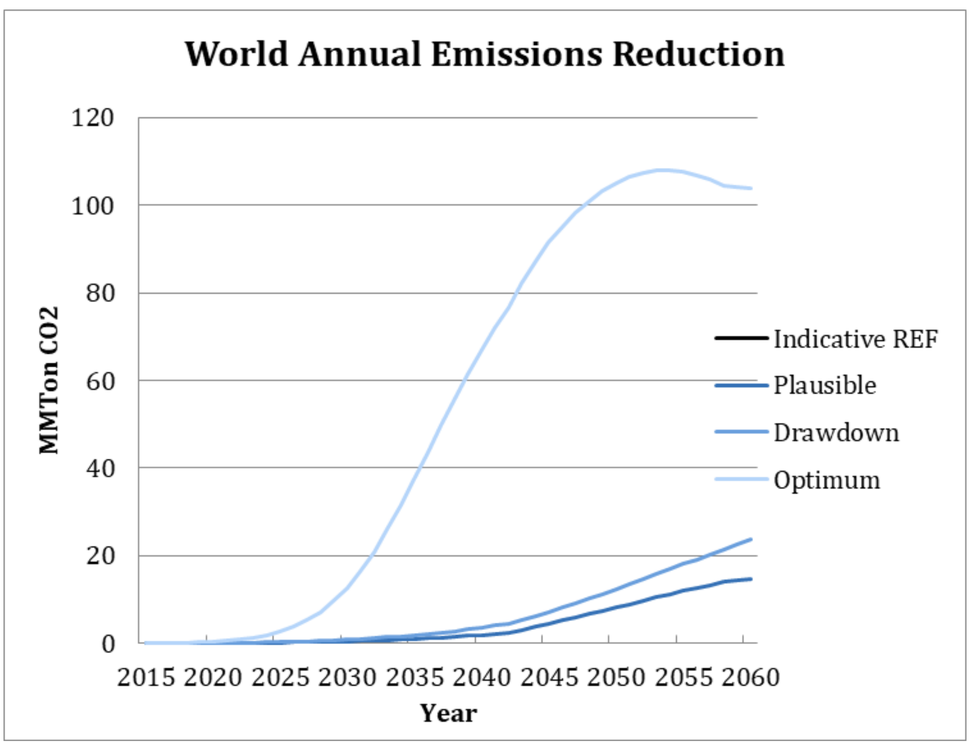


Figure 3.4 Green Roof World Annual Greenhouse Gas Emissions Reduction



3.3 Financial Impacts

Below are the financial results of the analysis for each scenario. For a detailed explanation of each result, please see the glossary.

Table 3.6 Cool Roof Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Cost Savings	Lifetime Operating Cost Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	1,224.31	79.47	179.25	425.14	64.13
Drawdown	1,938.18	137.18	338.77	735.57	115.10
Optimum	4,281.02	326.56	1,072.78	1,782.87	321.81

Table 3.7 Green Roof Financial Impacts

Scenario	Cumulative First Cost	Marginal First Cost	Net Operating Cost Savings	Lifetime Operating Cost Savings	Lifetime Cashflow Savings NPV (of All Implementation Units)
	2015-2050 Billion USD	*2015-2050 Billion USD*	*2020-2050 Billion USD*	*2020-2050 Billion USD*	*Billion USD*
Plausible	756.11	544.52	-17.95	-94.75	-166.40
Drawdown	1,099.80	817.54	-29.58	-142.76	-258.01
Optimum	8,761.20	6,849.98	-390.02	-1,212.70	-2,622.78

Figure 3.5 Cool Roof Net Profit Margin /Operating Costs Over Time

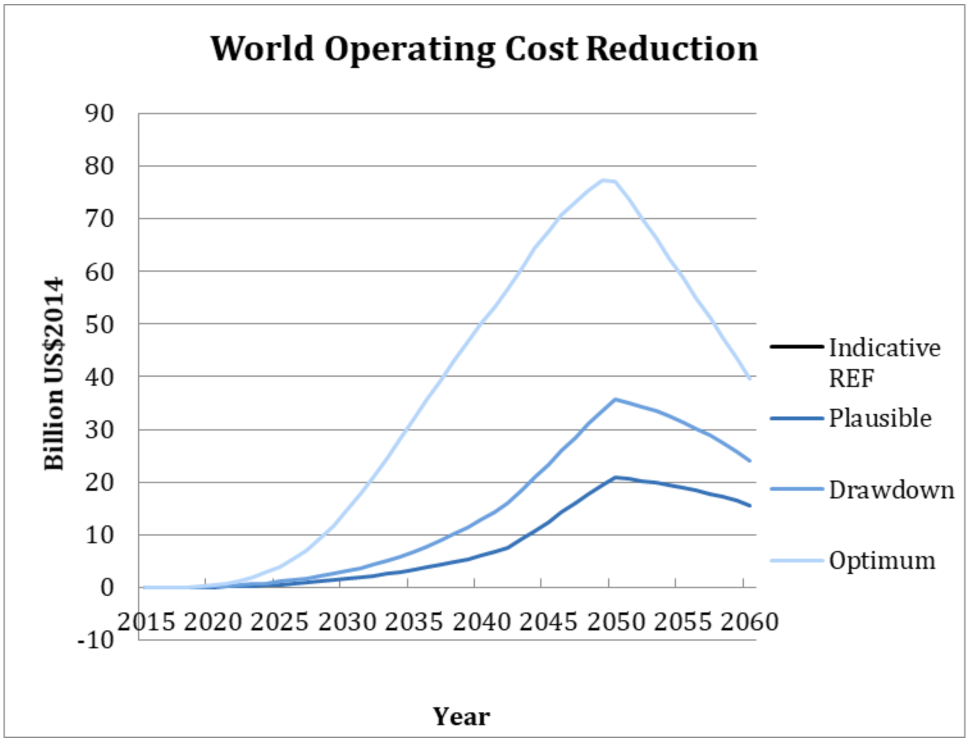
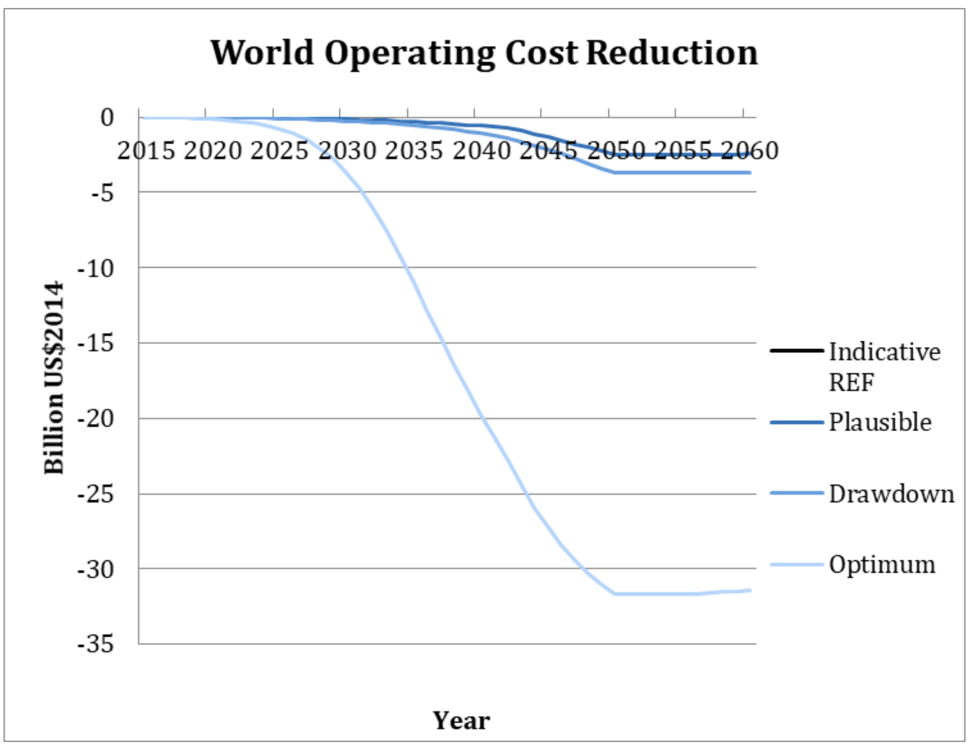


Figure 3.6 Green Roof Net Profit Margin /Operating Costs Over Time



4 DISCUSSION

Cool Roofs offer a zero- to low-cost, technically-proven path for reducing building space cooling loads and corresponding GHG emissions in Climate Zones (CZs) 0-4. Due to the "space heating penalty", cool roofs are not suited for most buildings in very cold climates. If widely adopted where applicable, Cool Roofs could reduce space cooling loads by approximately 9%. The result, in the Project Drawdown Optimum Scenario, would be installation of 142 billion m^2 of Cool Roofs by 2050, resulting in a reduction of 4.0 Gt of 2020-2050 CO_2 emissions compared with the reference Scenario. This would reduce atmospheric GHG concentration by 0.35 PPM CO_2-equivalent in 2050. Lifetime operating cost savings would total $1,783 from 2020 to 2050, with a lifetime cash flow savings NPV of $322B.

The number one challenge for global Cool Roof adoption, especially in developing countries, is a small first cost increment which can be a major barrier in low-cost applications. The key factors that have propelled Cool Roof market adoption include demonstration of functional performance and real-world economic value in the specific building context, development of products tailored to local needs, and establishment of building codes and product rating standards.

Green Roofs offer similar thermal impact to reduce building space cooling loads, and also provide insulation that can reduce space heating. Though having much higher first cost than conventional roofs, Green Roofs offer additional benefits, notably stormwater retention and mitigation, and the aesthetic of urban gardens. As living vegetated systems, Green Roofs with minimal irrigation are well-suited for CZs 3-6 and for the non-arid portions of CZs 0-2. If widely adopted where they are applicable, Green Roofs could reduce space cooling loads by approximately 10% and heating loads by 7%. The result, in the Project Drawdown Optimum Scenario, is installation of 45 billion m^2 of Green Roofs by 2050, resulting in a reduction of 1.3 Gt of 2020-2050 CO_2 emissions compared with the reference Scenario. This would reduce atmospheric GHG concentration by 0.1 PPM CO_2-equivalent in 2050, but *increase* lifetime operating cost by $1,213B from 2020 to 2050 and *increase* lifetime cash flow NPV by $2,623B.

Key barriers for Green Roofs include unsuitability of much of the existing building stock to bear the additional weight, high installation and maintenance costs, lack of supportive government policies and incentives, and lack of customer awareness and appreciation of the non-energy benefits of Green Roofs.

Given Green Roofs' first cost premium, government incentives that reduce Green Roof lifecycle cost are key to accelerating global adoption. Where Green Roofs have succeeded, notably in Germany and selected North American and Asian cities, success has been driven by government mandates / incentives for non-energy benefits, especially stormwater management, aesthetics, and biodiversity, and by development of the skill base and infrastructure needed to install and maintain Green Roofs.

Two areas of energy efficient roof impact that bear further investigation are:

- Urban Heat Island / albedo effect
- Direct CO_2 sequestration by Green Roofs

A number of researchers (notably H. Akbari, Matthews, Menon, Levinson, Seto, Rossi, Cotana, Filiponni et al., Millstein and Menon (2011), Oleson, Bonan, and Feddema (2010)) have modeled and/or reported on the potential impact of the increased albedo of a global urban building shift to cool roofs on global temperatures. The results of some of these models show significant global cooling. Akbari et al. (2009) estimates the effect at approximately 44 gigatons of CO2 offset. "Akbari et al (2012) and Akbari and Matthews (2012) report that increasing urban albedo by 0.1 is equivalent to onetime CO2 emission reductions of 25–150 Gt and 160 Gt CO2, respectively" (reported in Zhang 2016). Rossi et al (2013) suggest "1 m2 of surface which produces an increase in albedo of 0.5 compensates for, during its life cycle, the release in the atmosphere of approximately 250 kgCO2eq. The same surface, at 48 degrees latitude (e.g. Paris), compensates for the release of about 170 kgCO2eq."

Direct CO^2 sequestration by Green Roofs, as noted in the Literature Review, cannot be disregarded and bears further investigation.

4.1 Limitations

The main limitations on widespread Cool Roof adoption are a slightly increased first cost – a major barrier especially in developing countries – and lack of locally-appropriate products with proven technical functional performance and corresponding test methods and rating systems. Success in the USA over the last 20+ years was possible only via a long process of demonstrating technical impact and value, developing products suited to US roofing needs and tastes, and establishing Cool Roof building codes and standards. Products for developing countries will likely look quite different and take years to commercialize.

Green Roofs, in addition to the limits that Cool Roofs face, have a far higher first cost and are less economical in terms of energy / GHG impact. As a result, implementation has been driven primarily by non-energy-related benefits, especially storm water mitigation incentives and aesthetics. These factors and lack of uniform design and construction standards will continue to hamper Green Roof adoption.

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6 GLOSSARY

Adoption Scenario – the predicted annual adoption over the period 2015 to 2060, which is usually measured in **Functional Units**. A range of scenarios is programmed in the model, but the user may enter her own. Note that the assumption behind most scenarios is one of growth. If, for instance, a solution is one of reduced heating energy usage due to better insulation, then the solution adoption is translated into an increase in use of insulation. There are two types of adoption scenarios in use: **Reference (REF)** where global adoption remains mostly constant, and **Project Drawdown Scenarios (PDS)** which illustrate high growth of the solution.

Approximate PPM Equivalent – the reduction in atmospheric concentration of CO_2 (in **PPM**) that is expected to result if the **PDS Scenario** occurs. This assumes a discrete avoided pulse model based on the Bern Carbon Cycle model.

Average Abatement Cost – the ratio of the present value of the solution (**Net Operating Savings** minus **Marginal First Costs**) and the **Total Emissions Reduction**. This is a single value for each solution for each **PDS Scenario**, and is used to build the characteristic "*Marginal Abatement Cost*" curves when Average Abatement Cost values for each solution are ordered and graphed.

Average Annual Use – the average number of functional units that a single implementation unit typically provides in one year. This is usually a weighted average for all users according to the data available. For instance, total number of passenger-km driven by a hybrid vehicle in a year depends on country and typical number of occupants. We take global weighted averages for this input. This is used to estimate the **Replacement Time**.

Cumulative First Cost – the total **First Cost** of solution **Implementation Units** purchased in the **PDS Scenario** in the analysis period. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Direct Emissions – emissions caused by the operation of the solution, which are typically caused over the lifetime of the solution. They should be entered into the model normalized per functional unit.

Discount Rate- the interest rate used in discounted cash flow (DCF) analysis to determine the present value of future cash flows. The discount rate in DCF analysis takes into account not just the time value of money, but also the risk or uncertainty of future cash flows; the greater the uncertainty of future cash flows, the higher the discount rate. Most importantly, the greater the discount rate, the more the future savings are devalued (which impacts the financial but not the climate impacts of the solution).

Emissions Factor– the average normalized emissions resulting from consumption of a unit of electricity across the global grid. Typical units are kg CO_2e/kWh.

First Cost- the investment cost per **Implementation Unit** which is essentially the full cost of establishing or implementing the solution. This value, measured in 2014$US, is only accurate to the extent that the cost-based analysis is accurate. The financial model assumes that the first cost is made entirely in the first year of establishment and none thereafter (that is, no amortization is included). Thus, both the first cost and operating cost are factored in the financial model for the first year of implementation; all years thereafter simply reflect the operating cost until replacement of the solution at its end of life.

Functional Unit – a measurement unit that represents the value, provided to the world, of the function that the solution performs. This depends on the solution. Therefore, LED Lighting provides petalumen-hours of light, Biomass provides tera-watt-hours of electricity, and high speed rail provides billions of passenger-km of mobility.

Grid Emissions – emissions caused by use of the electricity grid in supplying power to any operation associated with a solution. They should be in the units described below each variable entry cell. Drawdown models assume that the global electric grid, even in a Reference Scenario, is slowly getting cleaner, and that emissions factors fall over time resulting in lower grid emissions for the same electricity demand.

Implementation Unit – a measurement unit that represents how the solution practice or technology will be installed/setup and priced. The implementation unit depends on the solution. For instance, implementing electric vehicles (EV) is measured according to the number of actual EV's in use, and adoption of Onshore Wind power is measured according to the total terawatts (TW) of capacity installed worldwide.

Indirect Emissions – emissions caused by the production or delivery or setup or establishment of the solution in a specified area. These are NOT caused by day to day operations or growth over time, but they should be entered into the model normalized on a per functional unit or per implementation unit basis.

Learning Rate/Learning Curve - Learning curves (sometimes called experience curves) are used to analyze a well-known and easily observed phenomenon: humans become increasingly efficient with experience. The first time a product is manufactured, or a service provided, costs are high, work is inefficient, quality is marginal, and time is wasted. As experienced is acquired, costs decline, efficiency and quality improve, and waste is reduced. The model has a tool for calculating how costs change due to learning. A 2% learning rate means that the cost of producing a *good* drops by 2% every time total production doubles.

Lifetime Capacity – this is the total average functional units that one implementation unit of the solution or conventional technology or practice can provide before replacement is needed. All technologies have an average lifetime usage potential, even considering regular maintenance. This is used to estimate the **Replacement Time** and has a direct impact on the cost to install/acquire technologies/practices over time. E.g. solar panels generate, on average, a limited amount of electricity (in TWh) per installed capacity (in TW) before a new solar panel must be purchased. Electric vehicles can travel a limited number of passenger kilometers over its lifetime before needing to be replaced.

Lifetime Operating Savings–the operating cost in the PDS versus the REF scenarios over the lifetime of the implementation units purchased during the model period regardless of when their useful life ends.

Lifetime Cashflow NPV-the present value (PV) of the net cash flows (PDS versus REF) in each year of the model period (2015-2060). The net cash flows include net operating costs and first costs. There are two results in the model: Lifetime Cashflow NPV for a Single **Implementation Unit**, which refers to the installation of one **Implementation Unit**, and Lifetime Cashflow NPV of All Units, which refers to all **Implementation Units** installed in a particular scenario. These calculations are also available using profit inputs instead of operating costs.

Marginal First Cost – the difference between the **First Cost** of all units (solution and conventional) installed in the **PDS Scenario** and the **First Cost** of all units installed in the **REF Scenario** during the analysis period. No discounting is performed. The number of solution implementation units that are available to provide emissions reduction during the analysis period is dependent on the units installed prior to the analysis period, and hence all implementation units installed after the base year are included in the cumulative first costing (that is 2015-2050).

Net Annual Functional Units (NAFU) – the adoption in the PDS minus the adoption in the REF in each year of analysis. In the model, this represents the additional annual functional demand captured either by the solution in the **PDS Scenario** or the conventional in the **REF Scenario**.

Net Annual Implementation Units (NAIU) – the number of **Implementation Units** of the solution that are needed in the PDS to supply the **Net Annual Functional Units (NAFU).** This equals the adoption in the PDS minus the adoption in the REF in each year of analysis divided by the average annual use.

Net Operating Savings – The undiscounted difference between the operating cost of all units (solution and conventional) in the **PDS Scenario** minus that of all units in the **REF Scenario**.

Operating Costs – the average cost to ensure operation of an activity (conventional or solution) which is measured in 2014$US/**Functional Unit**. This is needed to estimate how much it would cost to achieve the adoption projected when compared to the **REF Case**. Note that this excludes **First Costs** for implementing the solution.

Payback Period – the number of years required to pay all the **First Costs** of the solution using **Net Operating Savings**. There are four specific metrics each with one of **Marginal First Costs** or **First Costs** of the solution only combined with either discounted or non-discounted values. All four are in the model. Additionally, the four outputs are calculated using the increased profit estimation instead of **Net Operating Savings**.

PDS/ Project Drawdown Scenario – this is the high growth scenario for adoption of the solution

PPB/ Parts per Billion – a measure of concentration for atmospheric gases. 10 million PPB = 1%.

PPM/ Parts per Million – a measure of concentration for atmospheric gases. 10 thousand PPM = 1%.

REF/ Reference Scenario – this is the low growth scenario for adoption of the solution against which all **PDS scenarios** are compared.

Regrets solution has a positive impact on overall carbon emissions being therefore considered in some scenarios; however, the social and environmental costs could be harmful and high.

Replacement Time- the length of time in years, from installation/acquisition/setup of the solution through usage until a new installation/acquisition/setup is required to replace the earlier one. This is calculated as the ratio of **Lifetime Capacity** and the **Average Annual Use**.

TAM/ Total Addressable Market – represents the total potential market of functional demand provided by the technologies and practices under investigation, adjusting for estimated economic and population growth. For this solutions sector, it represents world and regional total addressable markets for electricity generation technologies in which the solutions are considered.

Total Emissions Reduction – the sum of grid, fuel, indirect, and other direct emissions reductions over the analysis period. The emissions reduction of each of these is the difference between the emissions that would have resulted in the **REF Scenario** (from both solution and conventional) and the emissions that would result in the **PDS Scenario**. These may also be considered as “emissions avoided” as they may have occurred in the REF Scenario, but not in the PDS Scenario.

Transition solutions are considered till better technologies and less impactful are more cost effective and mature.

TWh/ Terawatt-hour – A unit of energy equal to 1 billion kilowatt-hours