Cooler Than Cool Roofs:
How Heat Doesn't Move Through a Green Roof

A 7-part series on the fundamentals of energy and green roofs

by
Christopher Wark
Energy Editor, greenroofs.com

(This series was originally published at greenroofs.com April 2010 - April 2011)

Copyright 2011 Christopher Wark

Introduction

8 years ago, my wife, Wendy, and I attended the Chicago's Greening Symposium as part of our exploration into the world of roof gardening. At the time, I was researching fuel cell systems for Caterpillar and thermodynamics was fresh on my mind. So during the Q & A of a green roofing presentation at the Symposium, I had to ask what the energy benefits are of vegetating a roof. The answer was quick and almost terse: "There aren't any." My brain responded just as quickly: "That can't be right. I feel a mission coming on." Thus began a year-long endeavor to apply my mechanical engineering education and experience to unravel the mysteries of how heat moves through a vegetated roofing system.

The result was the creation of a computer program that describes, in detail, the heat transfer through any type of roof system, energy savings (or costs) associated with it, and the subsequent financial impact. At the time, validation was a challenge due to the dearth of instrumented green roof demonstration projects. In fact, the only one published by 2002 was the study done by the National Research Council Canada. Fortunately, this computer program, eventually dubbed Q-Calc, relied entirely on well-established engineering calculations and data, and as it turned out, was easily validated by some key plant biology research.

Shortly after attending Chicago's Greening Symposium in 2002, Wendy and I established SHADE Consulting (later renamed Green Roof Innovations). For the next 3 years we would provide a variety of green roof consulting services and develop 3 different modular green roof concepts, one of which has been picked up by a company in China. With SHADE/GRI, I had the opportunity to provide energy consulting for some prominent green roofing projects, including pilot programs for the City of Chicago, the City of Portland (OR), The City of New York, and projects for Earth Pledge, including the Silvercup Studios green roof.

In 2005, I moved on to do more whole-building and other specialty energy analysis, but green roofs still hold a special place in my heart. So I decided to spread the love and put together a primer following my discoveries of how heat moves through a green roof.

"Cooler than Cool Roofs: How Heat Doesn't Move Through a Green Roof" is a 7 part series explaining the key aspects of green roof heat transfer issues and the best ways to take advantage of a green roof's energy benefits. The topics that will be covered are:

1. The Essentials: Heat Transfer by Layer
2. Keeping Drought-Resistant Plants Cool
3. Evapotranspiration
4. When Weight is Good
5. Assuming Insulation
6. Green Roofs vs. Cool Roofs
7. The Green Roof Energy Secret and How To Use It

Some of this discussion applies to more than just vegetation systems. In fact, you may find it useful for any roofing system or exterior wall. All of the discussion is based on long-established textbook physics, very conventional building engineering, and a little bit of recent plant research.

I hope you enjoy this series and are able to get a few "Ah hah!" moments out of it, or at least gain a better appreciation for the complex nature of something as simple as a green roof.

1 - The Essentials: Heat Transfer by Layer

A few bad jokes come to mind that follow along the line of: insulation keeps hot stuff hot and cold stuff cold - how does it know? Well, how does it? You might be surprised at how few engineers can answer that question. You might also be surprised at how easily the answer can get a bit complicated.

But what is truly amazing is that plants, the active ingredient in a green roof, actually do know the difference between hot and cold and can do something about it in a lot of different ways. On the other hand, the layers below the foliage in a green roof system are not so smart, yet as we try to describe how heat moves through wet soil and heavy roof decks, we can quickly find ourselves in a quagmire of engineering math.

Instead of immediately fretting over math and engineering, let's first take a more personal look at energy and heat transfer. When we talk about energy in the context of temperature, we are talking about the movement of heat, or "heat transfer", from something warmer to something cooler (so says the 2nd Law of Thermodynamics), except in the cases of air conditioning (beyond the scope of this article) and sweating (otherwise known as evapotranspiration). When I get too hot, it is because heat from something hotter than my skin, like say, the sun, is threatening to cook me, so I take action to cool down. Plants do exactly the same thing. However, when an inanimate object such as my car gets too hot from sitting in the sun, it just keeps sitting there getting hotter because it is stupid, like dirt or asphalt or roofing shingles.

Shingles just sit there getting hotter.

To understand some key thermal characteristics of a green roof, it may also help to contemplate a few other heat-related experiences such as why the potatoes and carrots in my beef stew are still too hot even after the rest has cooled down. Or why frost is on the pumpkin even when the temperature at night stays above 32 degrees. The most important thing to remember is that whether through food, a building, or across the Earth, heat always moves in the same ways.

In this series, a few technical terms that may or may not be familiar or well understood will be used, so we should start with a very brief glossary of the different types of heat transfer:

conduction - The simplest way of moving heat from a hot molecule to a cold one. This is the kind of heat transfer you get through a solid material.

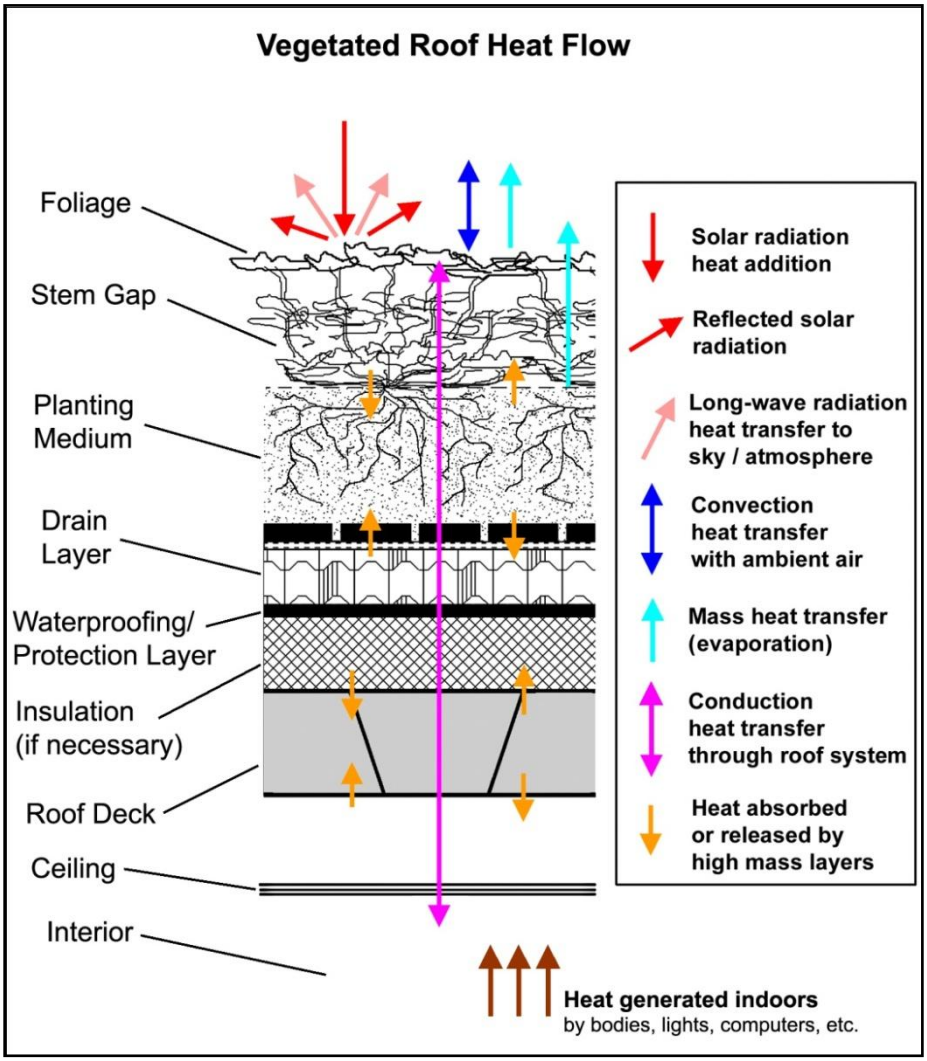
convection - Moving heat to or from a surface by way of a flowing gas or liquid. Cool wind blowing across hot food carries heat from the food out to the air faster than if you block it from the wind. Warm water flowing over cold hands transfers that warmth to your skin faster than dipping your hands into still water. The rate of heat transfer increases with flow rate, but in a way that can be tricky to analyze.

radiation - Electro-magnetic heat transfer from all warmer surfaces to all cooler surfaces. It is always happening throughout the universe, but the example we notice the most is solar radiation since the sun is always warmer than anything on the earth's surface (except when physicists go smashing atomic particles). Just as light is radiation, heat radiation can be reflected, absorbed, or transmitted through a surface as light through a window.

evaporation - A form of "mass heat transfer" because heat is removed by literally taking away hot material. In the case of a green roof, that material is water. A special characteristic of this type of heat transfer is that the material can be cooler than the surrounding air, making the wet surface a little cooler than the ambient air temperature.

thermal mass - The ability to store heat in something heavy, like a big rock or a chunk of steel or a potato. It is a simple concept, but describing mathematically how the heat comes and goes can be very difficult.

Armed with this rudimentary knowledge of heat transfer, we can begin to examine the smart and not-so-smart elements of a green roof. The following figure shows typical layers of a vegetated roofing system and all the ways heat moves through each layer.



Copyright 2011 Christopher Wark

Starting from the top,

1. Foliage – This is the most complex because it uses all methods of heat control provided by nature – convection, evaporation, conduction, solar reflectivity, radiative heat emission, and thermal mass. Plants can also utilize extra heat conserving strategies such as defoliation during winter.
2. Stem gap – The air trapped between the foliage and the top of the planting medium provides limited conduction and the stem itself conducts a small amount of heat between the foliage and the roots.
3. Media – Planting media conducts heat and often has enough thermal mass that it needs to be taken seriously. It can also cool through evaporation when adequately moist.
4. Drain layer – The amount of heat conduction through the drain layer depends on how wet it is. A more significant role of the drain layer can be through mass transfer - the removal of heat from saturated media by providing a drain path for water heated within the media. As an aside, this can also have the opposite effect in the winter by accelerating snow melt and preventing ice damming.
5. Waterproofing – The membrane provides simple conduction and some thermal mass.
6. Insulation (if necessary) – Insulation slows heat conduction and has negligible thermal mass.
7. Roof deck – Again, the roof deck provides simple conduction but can have significant thermal mass.

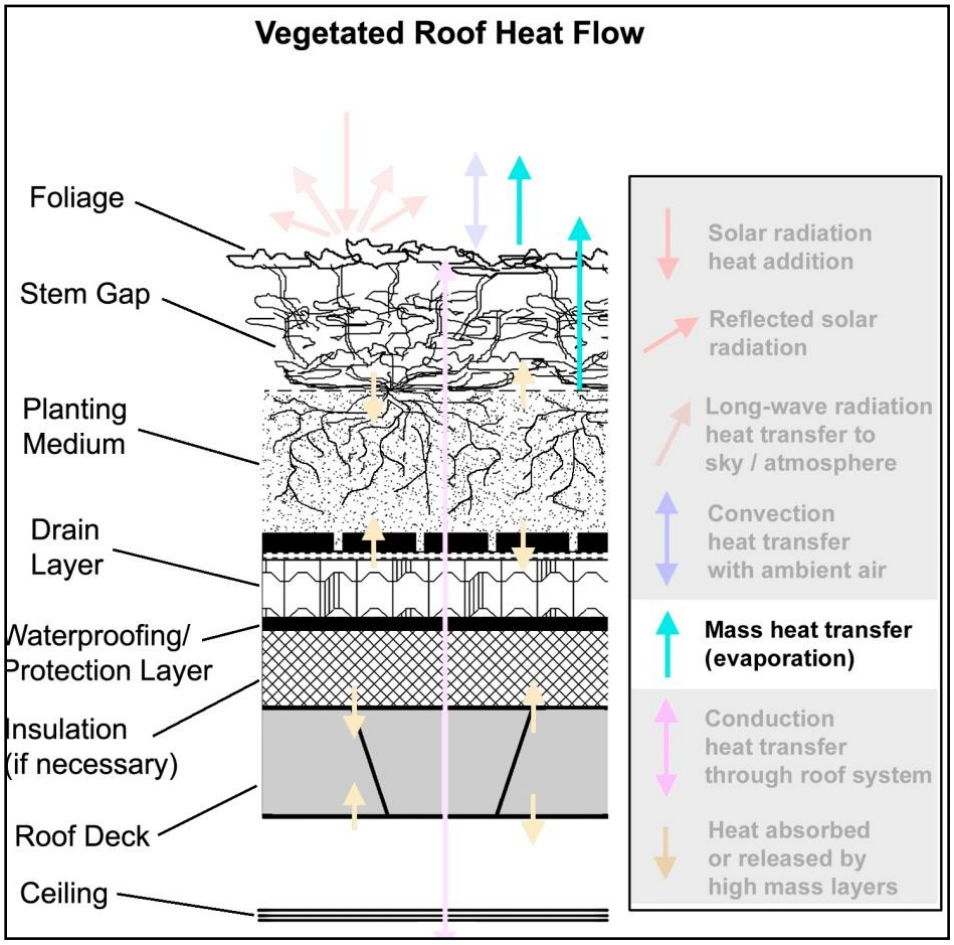
Figuring out how to optimize each layer is simply a matter of being smarter than the roof.

A green roof with good energy saving potential and a lot of style.

Through the next 6 sections, each of these areas will be explored in greater detail along with discussions of their applications and misapplications. References providing the background and expanded analysis of each topic are found at the end of the series. In the next section, we look at the thermal half of evapotranspiration, otherwise known as "green roof sweat".

2 - Evapotranspiration

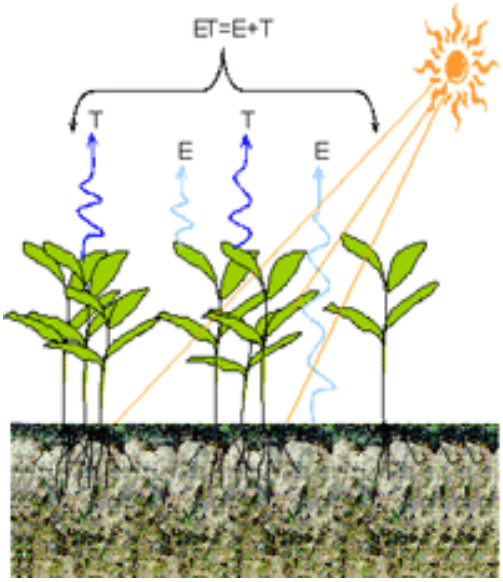
Anyone delving into the world of green roofs will hear the word "evapotranspiration" sooner or later. Sure, it's fun to say, what with all those syllables (as many as 7), but what does this word mean? Evapotranspiration can be thought of as vegetation's version of sweating. In short, it is the transport of water to the stomata, or "pores", of a leaf where it evaporates, plus the evaporation of moisture sitting elsewhere on the foliage and soil, all of which help cool the plant. In Section 1, I referred to evaporation as one way in which heat energy is removed from a green roof and evapotranspiration is the more specific term for the way evaporation removes that heat. For those who want to spend a little more time diving into the details of this topic, some websites with excellent primers on evapotranspiration are found in References 6 through 10 at the end of this series.



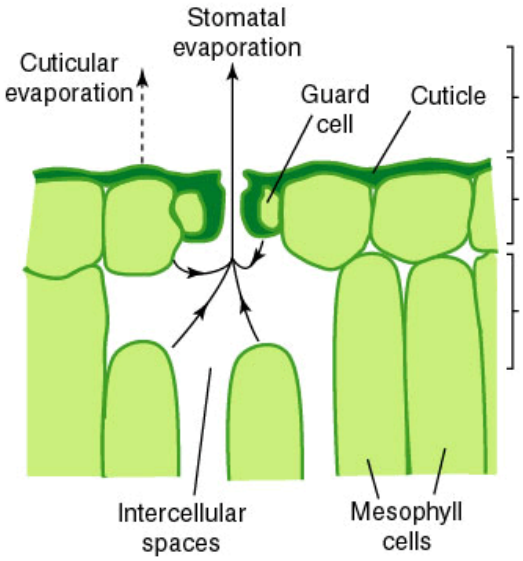
Copyright 2011 Christopher Wark

Another important question: why am I dedicating an entire month's worth of thought and typing to a single, specialized form of heat transfer? The answer is purely anecdotal. When the subject of energy and green roofs comes up, nearly everyone familiar with the topic will tell me that green roofs stay cool because of evapotranspiration. Why, even when discussing it with professional engineers doing building energy modeling, they assume that most of the cooling ability of a green roof is through evapotranspiration. Some of them completely ignore the 4 other ways in which the vegetation of a green roof deals with excess heat energy, which results in big analysis errors. We need to put the importance of evapotranspiration in perspective and start by trying to understand what it is and where the idea of its significance comes from.

Evapotranspiration is actually a combination of 2 words: evaporation and transpiration. Let's look at transpiration first. It is the process by which water is pumped from the soil (or planting medium) through the roots, up through the stems and out through the leaves by means of the force of evaporation at the tiny stomatal openings. The physics of how the force of evaporation at a stoma is strong enough to suck water up through the roots is pretty impressive and not easy to understand. As for evaporation, it is exactly what it sounds like – the actual evaporation of water from the surfaces of the leaves, stems, and soil.



(*California Dept. of Water Resources)*



(John A. Dutton e-Education Institute, Pennsylvania St. U.)

In figuring out how much evaporation contributes to the cooling of a roof, we need to know the amount of heat carried away from the stoma and all of those other surfaces. Calculating evaporation rates in such a complex environment is, well, complex; however, we can get a pretty reasonable number based on a fundamental physical law: Conservation of Mass. Conservation of Mass simply states that the amount of water evaporating from a roof must equal the amount of water put on the roof by rain, irrigation, dew, etc. In fact, many farmers in dry regions rely on established evapotranspiration calculations and data to determine how much irrigation is required to keep their crops alive. For instance, an alfalfa farmer in Kansas can expect to dump about 0.2 inches, or about half a pound per square foot, of water per day on his crop during July to make up for water evaporating away through transpiration (see Ref. 11). Half a pound of liquid water goes in through the roots, half a pound of water vapor comes out through the stoma to carry away the heat (thus the term *mass heat transfer*). The heat needed to evaporate that half pound of water is the amount of heat removal we are calculating.

Ah, but a sedum-covered extensive green roof in Boston is not the same thing as an alfalfa field in Kansas, now, is it? Although several blatant differences come to mind, our focus on evaporation energy ultimately directs us to the effects of planting media depth. For one thing, alfalfa roots want to travel down through several feet of topsoil while many sedums are quite content in just a few inches of a planting medium, which is one reason why alfalfa is a poor candidate for green roofs (for those not hip to the details of green roof construction, *planting media* should never be confused with *soil* and should never, never, ever, ever be referred to as *"dirt"*). For another thing, the Kansas field can hold then transpirate a whole lot more storm water than a shallow green roof.

Alfalfa field in Kansas *(cowbones.com)*

Four Seasons Hotel, Boston *(greenroofs.com)*

Before we abandon our alfalfa crop, let's take a quick look at how much heat is transferred away from that field on a hot summer afternoon through evapotranspiration. Using the Penman-Monteith equations to determine evapotranspiration rates (see Ref. 12) and then energy content equations or tables from one's thermodynamics textbooks (see Refs. 1 through 3) or relevant Wikipedia page (see Ref. 13) to calculate the evaporative heat loss, one should come to the conclusion that evapotranspiration only removes about 1/3 of the excess heat coming in from the noontime sun. So evapotranspiration is clearly not alfalfa's primary method of staying cool even though it has deep roots and plenty of water. To keep the crop from cooking before sunset, the other 2/3 of the solar heat must be dealt with by other means such as convection to the air, radiation emission to the sky, and a little bit of conduction back into the ground. Note that we are only talking about excess heat, not the 5% to 10% of sunlight that is used for photosynthesis by fast growing plants like alfalfa or garden crops like lettuce and tomatoes.

How does this compare with our sedum covered green roof in Boston? Assuming that the established sedum's water needs are satisfied by typical rainfall amounts, we can crank through the same equations used for the alfalfa crop to conclude that our non-irrigated green roof uses evapotranspiration to rid the roof of only 10% of the solar heat. Considering that the sun can account for about 95% of the excess heat coming in through a roof, evapotranspiration alone would lower the temperature of a typical extensive green roof by only a few degrees and leave us with a bunch of fried sedum. In reality, all of that solar heat energy *does* get dissipated through the 4 other ways described in the last section, along with evapotranspiration.

But if you are a huge fan of evapotranspiration and insist on utilizing it as your primary source of roof cooling, you can always install the equivalent of a hydroponic garden and essentially turn the roof into one big swamp cooler. Good luck with the water bills.

The moral of this story is that we need to pay more attention to all those other ways of moving heat away from a green roof if we want an accurate picture of how a green roof stays cool, particularly for low-maintenance extensive systems. Do you think we can learn something from desert plants? I think we can. In the next section, the spotlight is on survival techniques of drought-resistant plants.

3 - Keeping Drought-Resistant Plants Cool

When I first started to research the thermal properties of plants, I was immediately drawn to the ones that thrive on extremely limited water availability – desert plants – particularly those in the southwestern states where daytime outdoor temperatures can be dangerously hot in the shade and stupid hot out in the sun. It is in the lower deserts of this region that we find plants that have been photosynthesizing quite happily in the driest, sunniest, 120 degree heat since before the advent of sprinkler systems. In the desert, nature simply doesn't provide enough water year-round for plants to rely on evapotranspiration for cooling. So what kind of plants can thrive under these conditions and how do they cope with too much heat and not enough water?

The first plant most people would think of is a cactus with its pulpy stems, tough skin, and lots of big, sharp needles. But cacti, aloes, and other succulents fall into just one category of the following four different strategies used by desert plants:

1. **Drought-escaping plants** – Annual plants, such as wildflowers, that escape drought conditions altogether by going through their entire life cycle during a single rainy season (however short that may be). The rest of the time, when no water is available, only the seeds exist while waiting for the next rain.

monkey flower (*CWNP.org*)

2. **Drought-evading plants** – non-succulent plants that ride out periods of drought. They simply stop growing, go dormant, or possibly die back when water is no longer available. Some species, like the desert lily, maintain a large pulpy root while the rest of the plant may go dormant.

desert lily with roots (*CWNP.org*)

3. **Drought-enduring plants** – shrubs that keep growing even in times of extreme drought. They have extensive root systems that are usually shallow to capture occasional surface condensation and prohibit other plants from growing within several feet and competing for water. They stay cool by having small, pointy leaves. More on that later. The best, and possibly most widely studied example is the creosote bush.

Young creosote bush (*Wikimedia Commons*)

4. **Drought-resisting plants** – succulent perennials that store water in their stems, as in the case of cacti, or in their leaves, as in the case of aloe or (Tada!) sedums.

Succulents on the HSBC green roof, Mexico City (*greenroofs.com*)

The first two groups are not great candidates for low-maintenance green roof designs since their thermal protection for the building is greatly diminished during the hottest months. Even worse, they may not adequately stabilize the planting media, keeping it from blowing or sliding away. Green roofs designed with these plants pretty much just look like a vacant lot for most of the summer until local weeds take over (*not* necessarily a bad thing), so let's take a closer look at groups 4 and 5.

Even though drought-enduring plants tend not to work so well for green roofs since they typically inhibit the establishment and growth of other plants near them, their means of managing extreme heat is of great interest. Yes, they are able to collect and use water more efficiently than any other desert plants, but not enough to cool the plant, only enough to sustain photosynthesis. And yet, even with the sun beating down on them all day, the surface temperature of their leaves rarely rises more than a few degrees above the ambient air temperature.

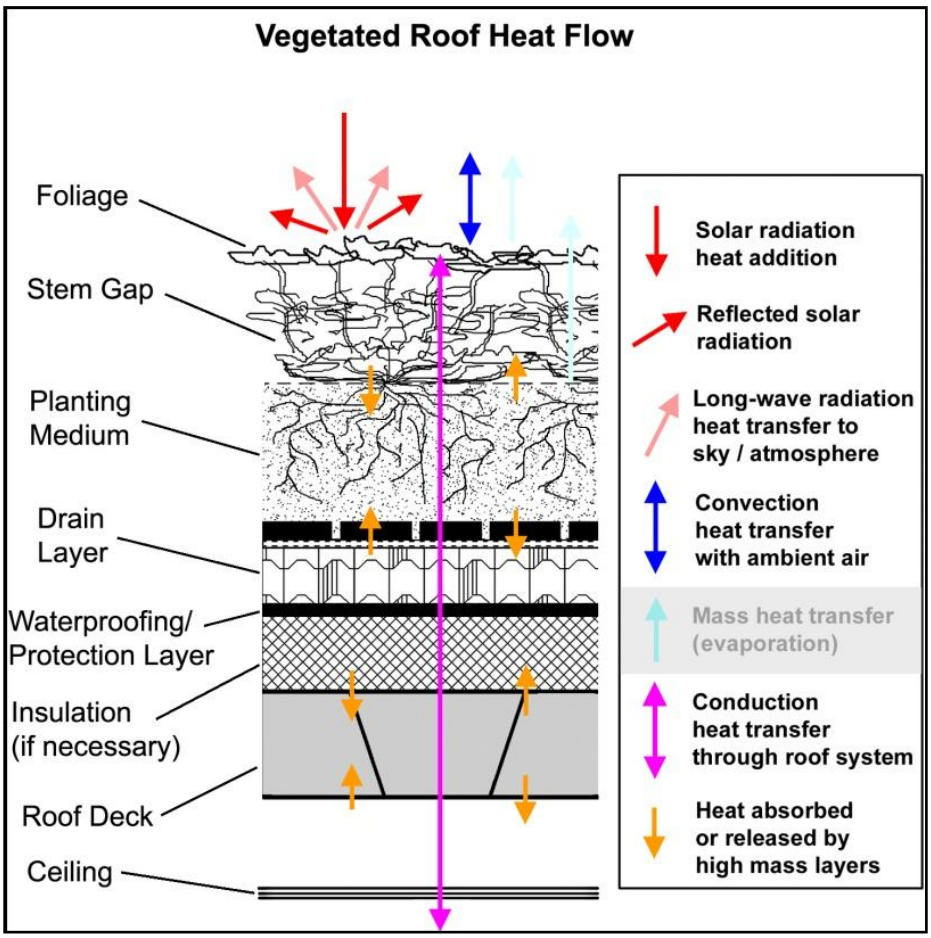
This is where the small, pointy leaves come in. In some cases they are small compound leaves. The size and shape of these leaves are optimized for maximum convection between the leaves and surrounding air - any excess heat from the sun is quickly transferred to the air by even the slightest air movement across each leaf. They are also good at minimizing the overall intensity of the sun by partially shading each other during different parts of the day or by angling or curling away from the sun. On a roof, this means planting medium surface temperatures beneath these plants will not be higher than the ambient air temperature. Sure, it helps that these plants have adapted leaves that can live with 120 degree temperatures, but if they were large and horizontal, without access to copious amounts of water, their mid-day leaf temperatures would climb until the leaves were no longer large or horizontal.

Drought-resisting plants (succulents) use a completely different set of tactics. They are best known for swelling with water when it is available and saving it for a few hundred sunny days. Again, this water is usually not transpired during the day for cooling. In fact, transpiration typically only occurs at night when it is safer for the plant to open its stoma and breathe. It is the stored water that provides thermal mass which helps control the plant's temperature - the water is able to absorb an impressive amount of heat during the day and release that heat at night. A large saguaro cactus may hold so much water that the temperature of its core can stay about half way between the average day and night temperatures through most of the dry season. The high water content also provides good heat conduction down to the ground.

But water storage isn’t the only way in which succulents manage excess heat in harsh desert climates. Most succulents also have a glossy or waxy leaf or stem surface that reflects sunlight. In many cases, the surface can get more reflective as the drought wears on.

And how about those needles? They do more than keep a cactus from being eaten. The needles can act as cooling fins, conducting heat out away from the outer body of a cactus to where the wind can remove the heat more efficiently through convection. Some smaller cacti, which do not have as much thermal mass, have adapted small, densely packed needles that help hold an insulating air layer at night and into the morning while partly shading the body during the day. The insulating needles also allow these cacti to endure freezing conditions much more effectively than cacti with sparse needles. The "fuzz" seen on the surface of many other succulents is simply an even smaller version of the compact needles.

Again, when these plants are used on a green roof, they guarantee that the planting medium beneath them will remain at or below the ambient air temperature since they are able to stay near the air temperature throughout the day.



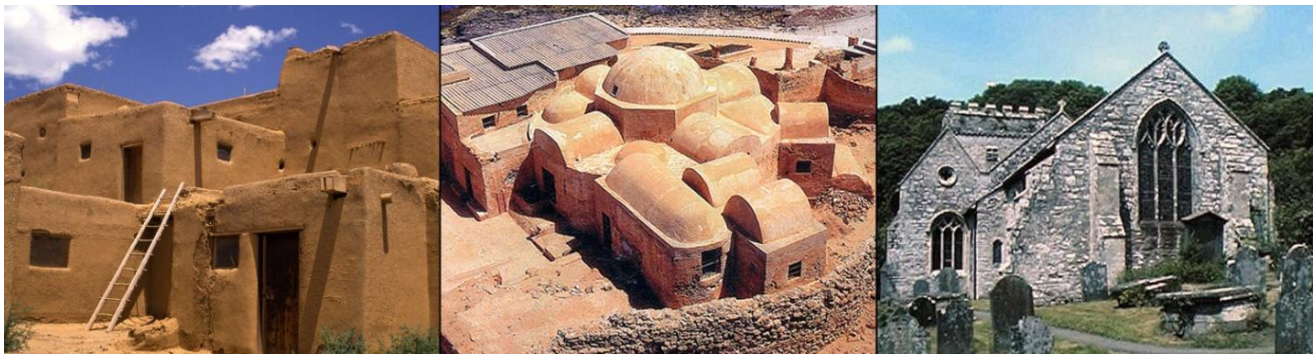
Copyright 2011 Christopher Wark

I have only pointed out a few of the wide variety and combinations of survival tools used by desert plants. The heat management examples used here included tactics for using convection (creosote bush leaves), conduction (cactus core), reflection (succulent skins), and thermal mass (water stored in succulents), all of which were introduced at the beginning of this series. The upshot is that evapotranspiration is not necessary for a green roof to thrive or provide energy benefits for the building it covers. Even though nature provides 5 different ways to move heat, it turns out that 4 out of 5 ain't bad.

Next up: the discussion gets "heavy".

4 - When Weight is Good

The weight of a green roof can sometimes present a structural challenge, but for controlling the flow of heat energy, that weight is a big benefit. If it is heavy enough, a roof system can take advantage of a material property called "thermal capacitance" to absorb heat during the day and then release it at night. For some applications, like building design, this property is also known as "thermal mass" because it is related to weight and specifically refers to the amount of heat per pound that can be absorbed or released. Classic examples of where thermal mass is an advantage in buildings include adobe houses in the Southwest U.S., masonry buildings in the Middle East, and heavy stone structures in northern latitudes, all of which temporarily store the day's heat in their heavy walls.



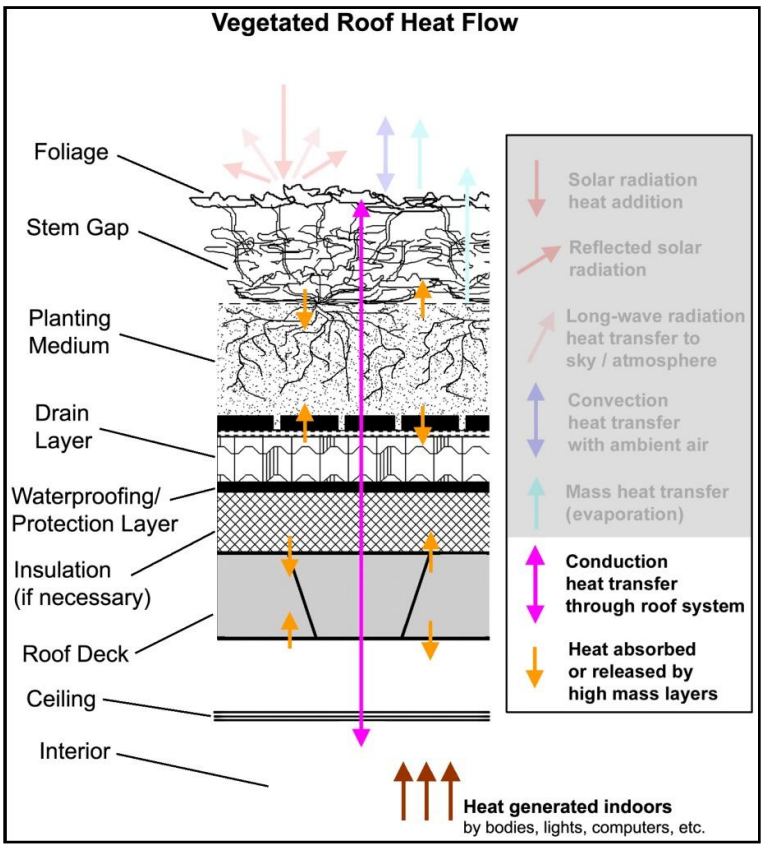
Taos adobe village North African villa Welsh stone church

But thermal mass is not just for buildings. It is universal, which means every object in the universe absorbs heat when its surroundings are hotter and releases that heat when the same surroundings cool down. A brick oven also takes advantage of thermal mass by collecting the flame's heat into its dense brick and transferring that heat back out to food placed in the oven. Speaking of food, remember that mention of hot potatoes in the Introduction? Potatoes can take longer to cook and then hold their heat longer than many other foods because the fiber in potatoes has high thermal capacitance and they hold a lot of water, and also because potatoes are sort of round (shape is very important in holding heat but beyond the scope of this article; however, it is not beyond the scope of Refs. 1 and 2). The "hold a lot of water" part is no coincidence - water has the highest thermal capacitance of any common substance on earth.

Chef Barry Horton *foodists.ca* (Hungry yet?)

Water also provides an excellent analogy for thinking about how thermal mass works since mathematically, water and heat flow in much the same way. Think of a green roof as a heat sponge - just as a green roof can soak up rain water and then drain or evaporate that water slowly, it does pretty much the same thing with heat.

Let's take our sponge analogy one step deeper into a little thought experiment. Think of a dry sponge sitting on a dry wooden cutting board in a sink. Now drip water on the sponge for several minutes. Depending on the absorptivity (now there's a word for paper towel ads!) and thickness of the sponge, water may have started to soak all the way through, making the wood wet, but not by much because most of the water gets stored in the sponge. After the dripping stops, eventually the sponge will dry out with some more of the water soaking into the wood and the rest evaporating. In the same way, a green roof will absorb heat from outside and then slowly release that heat back outside (and possibly inside) when it cools off, usually at night.



Copyright 2011 Christopher Wark

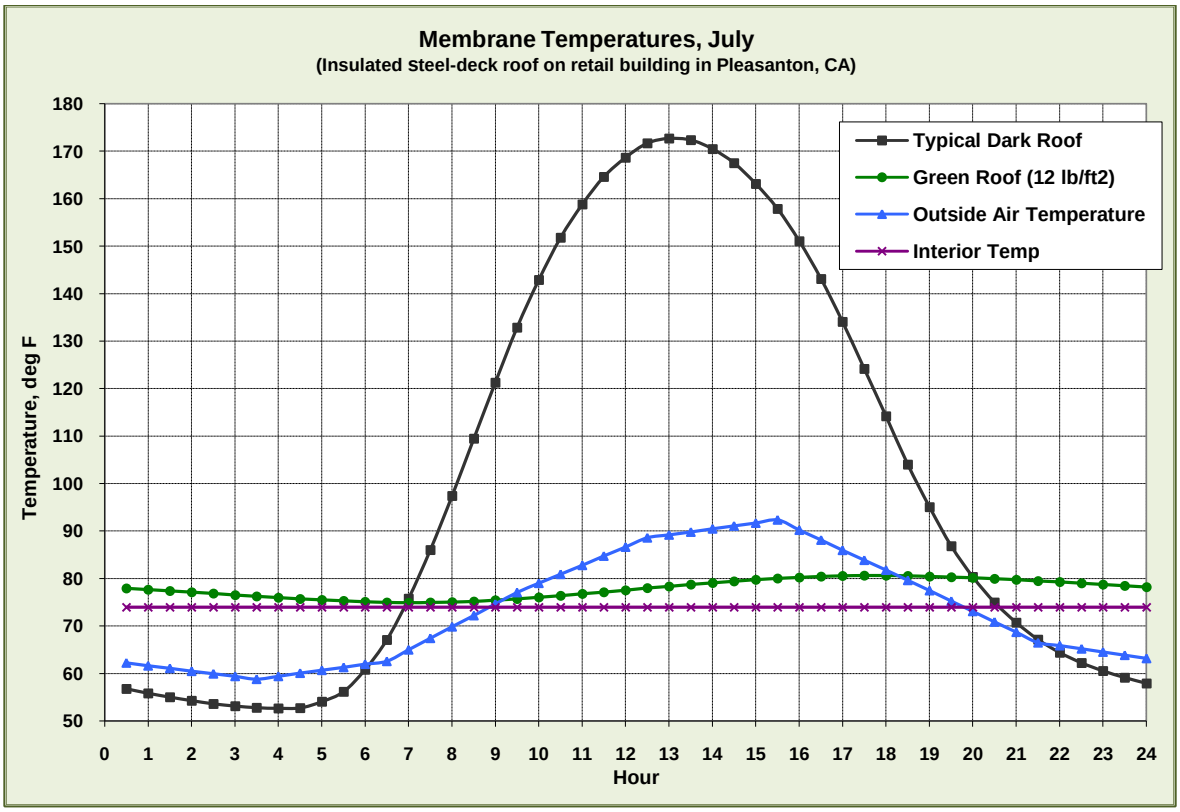
The weight of the deck, medium, and plants determine nearly all of the total thermal mass.

LiveRoof® cross-section

Again, thermal mass is associated with weight, not size. A 3 inch deep green roof with heavy planting medium and pulpy sedum may have more thermal mass than a 6 inch deep system with light-weight medium and wildflowers. So if an engineer were to calculate if a green roof could collect an entire day's heat, they would need to know its weight per square foot, regardless of thickness.

Speaking of engineers, this is where we start getting into the calculable aspects of moving energy through a green roof. If an engineer knows what he or she is doing, that engineer can include the roof insulation (if any) with the rest of the materials' thermal capacitance in their equations to come up with a number known as a "time constant" which describes how fast a roof system can absorb heat. For example, if it takes 12 hours to go from the coolest to the warmest outside temperature within a day, then the engineer should design the entire vegetated roof system to have a time constant of about 6 hours, depending on location. If done right, the center of the roof system will remain very close to the seasonal average ambient temperature with all diurnal (day and night) temperature swings eliminated.

To illustrate, the graph below shows results from an energy model of a green roof in Northern California. The green roof (green line) helps hold the roof temperature very close to the temperature inside the building (purple line), while the dark, exposed roof (black line) swings from cool at night to way too hot during mid-day. The time constant for this roof system was about 5 hours.



Copyright 2011 Christopher Wark

It seems that I have finally used the word "insulation" in our discussion of energy and controlling heat. I am about to use it a lot more in the next section.

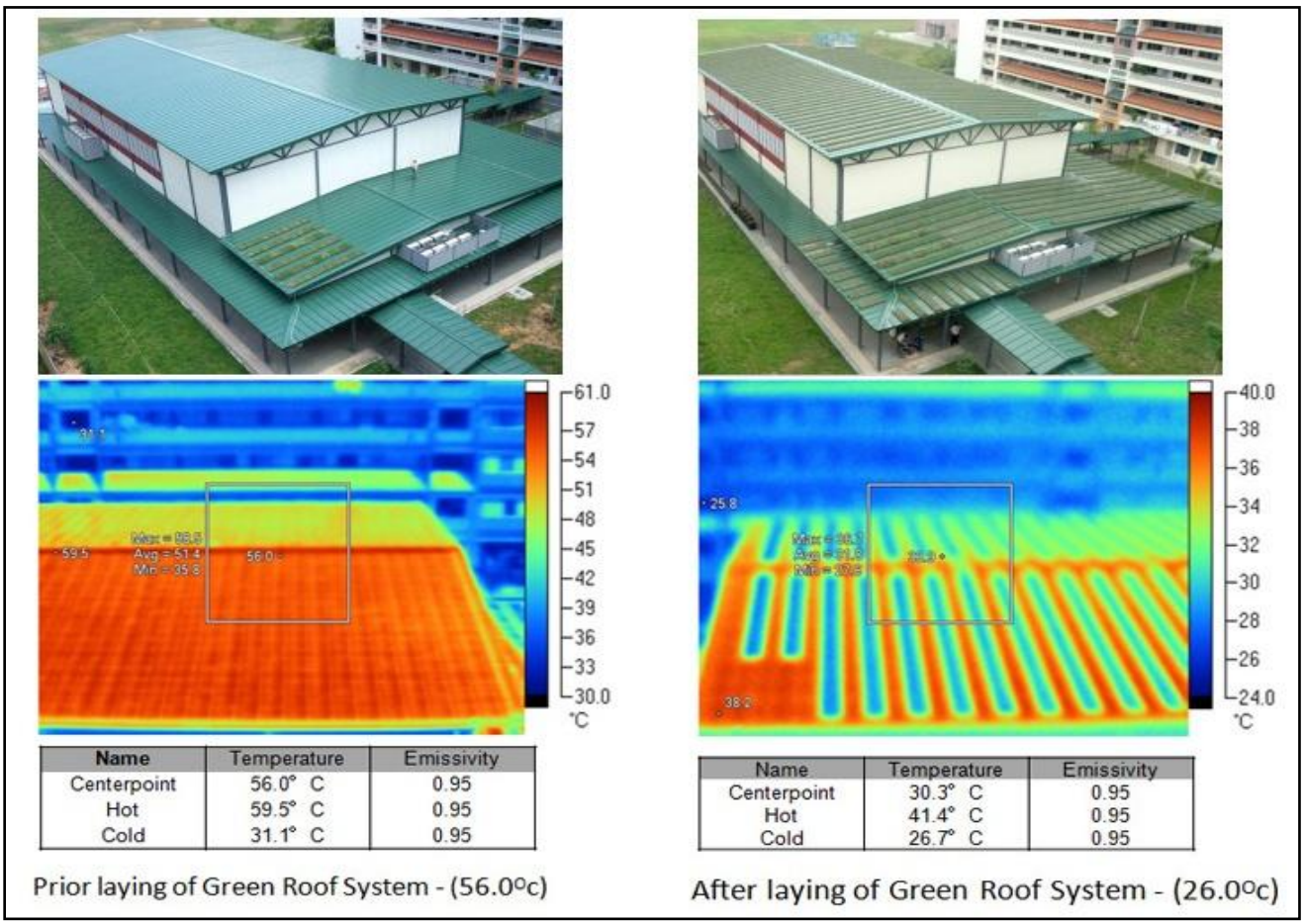
5 - Assuming Insulation

You may ask, "How well does a green roof insulate a building?" “What is the R-value of a green roof?” “More insulation is better, right?” "Does a green roof system have to include insulation?" “Don’t engineers already figure this out for us?”

You sure ask a lot of questions about insulation, so I suppose it is time to address each one:

"How well does a green roof insulate a building?"

The ability of a green roof to help keep a building cool during the summer and warm in the winter depends on the design and location of the building, as well as the type and construction of the green roof.



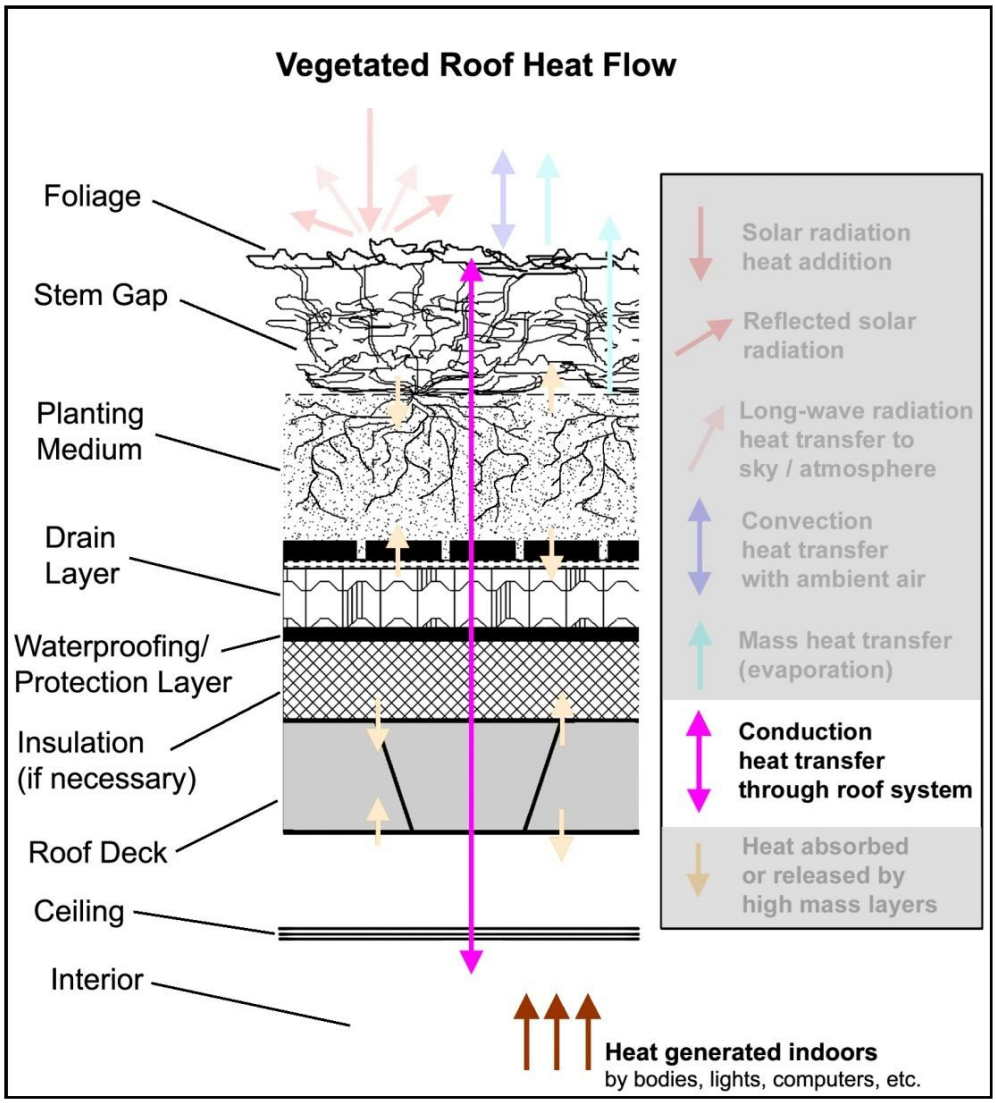
Most of the green roof heat management happens right at the surface. (*cleens.com*)

Note that the previous sentence does not include the word "insulate" but does contain the word "depends". In fact, understanding how to rate the ability of a green roof to manage heat energy has as much to do with language as it does with learning heat transfer. In order to make sure we are all clear on how insulation works, particularly in a green roof system, we need to take a little journey through the lexicon of insulation terminology, starting with:

"What is the R-value *of a green roof?"*

The most common request I get from architects and engineers is for the R-value of a green roof system. Unfortunately, the ability of a green roof to control the flow of heat energy cannot and should not be described only by an R-value, not even an "adjusted", "equivalent", or "approximate" R-value.

The term "R-value" has a very specific meaning. The "R" stands for *resistance*, as in *thermal resistance*. Physically, this describes nothing other than a simple restriction to heat flow, regardless of direction, which is one of the less-significant thermal properties of vegetation and its media and drain layer. So far in this series, I have described a number of ways that different elements of a green roof *manage* heat along with simple resistance to heat conduction - evaporation, reflection, convection, and thermal mass. Like an R-value, each of these has its own "value", "coefficient", or "dimensionless number" associated with equations that describe how they affect heat flow. They are beyond the scope of this article since some are represented by Greek letters that are difficult to type.



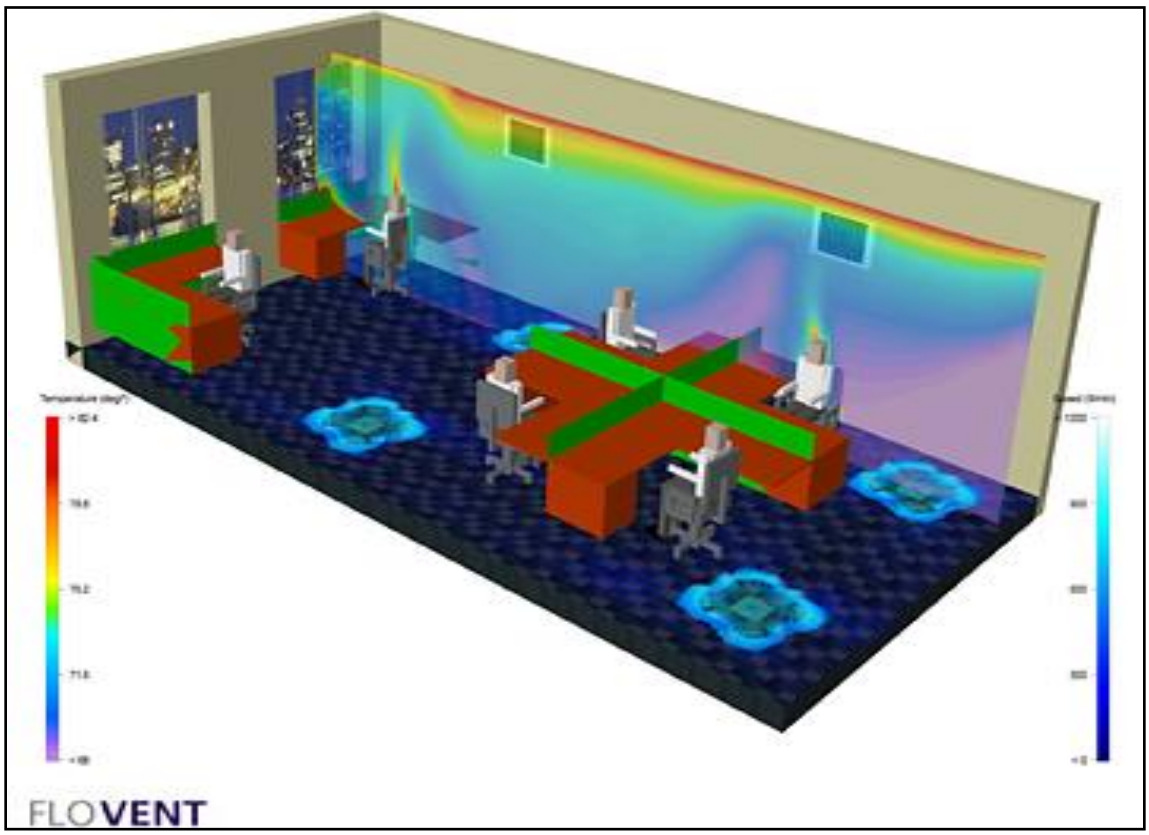
Copyright 2011 Christopher Wark

Mathematically, the heat conduction equation that properly uses an R-value is also very simple, whereas the equations that describe energy transfer through evaporation, reflection, convection, and thermal mass can get ugly. Unfortunately, plants and soil don't care about math. They insist on constantly adapting to their environment in complex, directional ways that can only be described using a combination of the nastier mathematical methods and formulas.

A green roof does not just sit there resisting heat flow, it is an *active energy device*, literally collecting, processing, and releasing energy according to its immediate need, just like all other living things, including people. Now for a good rhetorical question: What is the R-value of a human?

"More insulation is better, right?"

It depends. Unlike vegetation, regular old foam, batt, or cellulose insulation does actually just sit there resisting heat flow. It is wonderful at slowing down heat loss during winter but that is not necessarily enough reason to rely on it exclusively throughout the year. For example, let's say a lot of heat is already being generated inside a building by people, lights, computers, copiers, etc. (it is easier than you think). That *internal heat generation* might be useful in January in Minneapolis but during spring, autumn, and summer, it works best to let the heat escape, which can be accomplished with designs that utilize less insulation. As I have learned from whole-building energy and CFD modeling, much more insulation than necessary is often installed in many buildings located in milder climates.



FloVENT CFD temperature and air flow profiles for a typical office area

"Does a green roof system have to include insulation?"

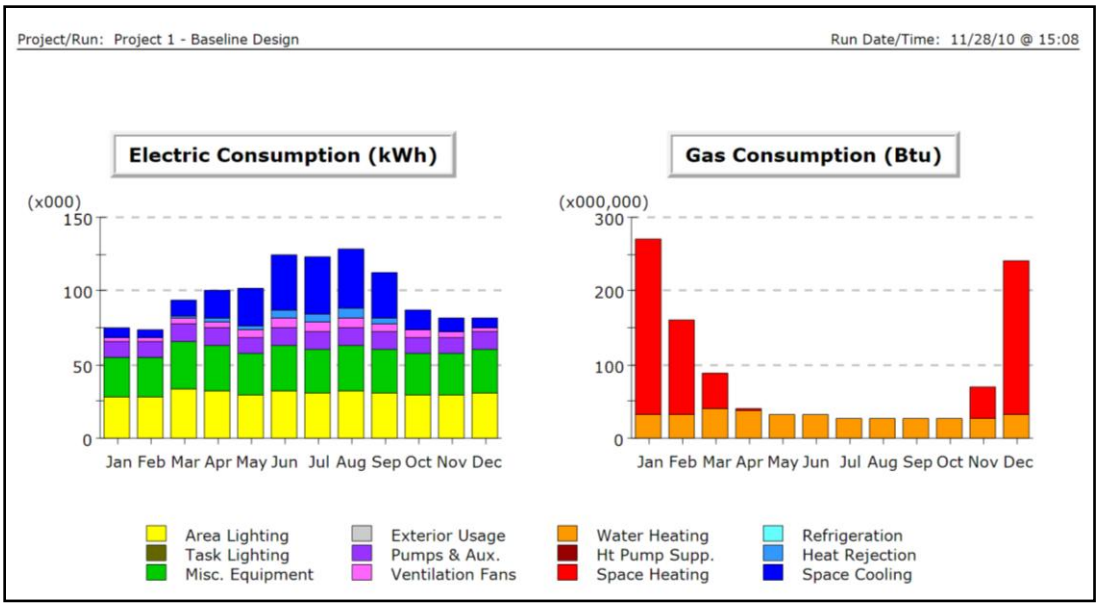
It depends. Since most of the green roof heat management happens right at the surface - in the vegetation and the planting media - any additional energy conservation measures that go underneath the drain layer should supplement the vegetation/media heat management, not the other way around. Also keeping in mind that heat flows in both directions, the amount of insulation you might put under your green roof should be calculated for your specific building and location before assuming how much is necessary, if any.

So the short answer to your question is: of course not - unless, of course, your local government tells you that it must (and how much).

InterNACHI, nachi.org

"Don't engineers already figure this out for us?"

Since every building is unique and the energy effectiveness of any green roof is totally dependent on the building's design and location, the energy savings associated with a green roof can only be determined as part of a whole-building energy model - the kind typically needed for LEEDtm certification.



eQUEST© (DOE-2.2) report

Commercial building owners have 2 choices:

1. hire an energy analyst who actually understands green roof thermal properties to model the building and conduct a proper roof treatment study, or
2. simply guess at how much the roof system design will affect energy use.

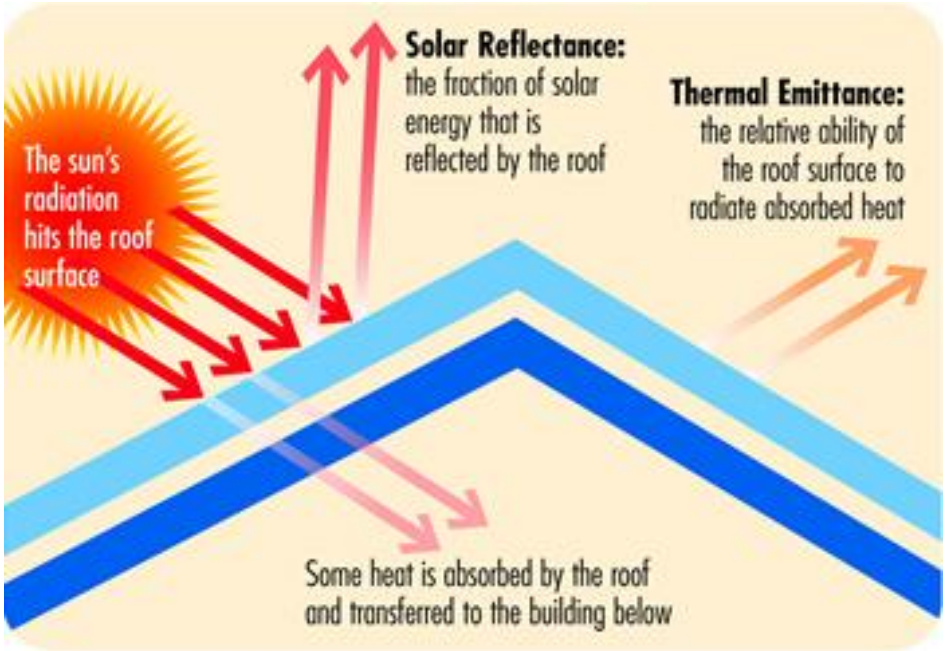
For a typical home, building codes usually already dictate the amount of insulation required. However, for a project such as a 50,000 square foot low-rise office building in St. Louis, guessing could be a $200,000 gamble; but gambling is fun, right?

Green roofs are not the only roof treatment that cannot be described by an R-value and whose energy performance is highly dependent on location. To a certain extent, "cool" roofs suffer a similar lack of thermal simplicity. We will take a look at those similarities and a couple of important differences in the next section.

6 - Green Roofs vs. Cool Roofs

Cool roofs are pretty cool, but whether or not they save as much energy as a green roof requires, as usual, a closer look at a) a cool roof, and b) a given green roof design.

First we need to review what makes a cool roof cool. As illustrated below, when sunlight hits the surface of a roof, some of it is reflected back into space (or into a neighboring building) and the rest is absorbed into the roof. For example, a common roof surface may reflect 30% of the sunlight and the laws of thermodynamics say that the remaining 70% must be going through the surface and into the rest of the roof structure. Referred to as the roof's "reflectivity", it is the simplest form of an "energy balance". This includes all wavelengths of sunlight: visible light, ultraviolet radiation, and infrared (long-wave) radiation.



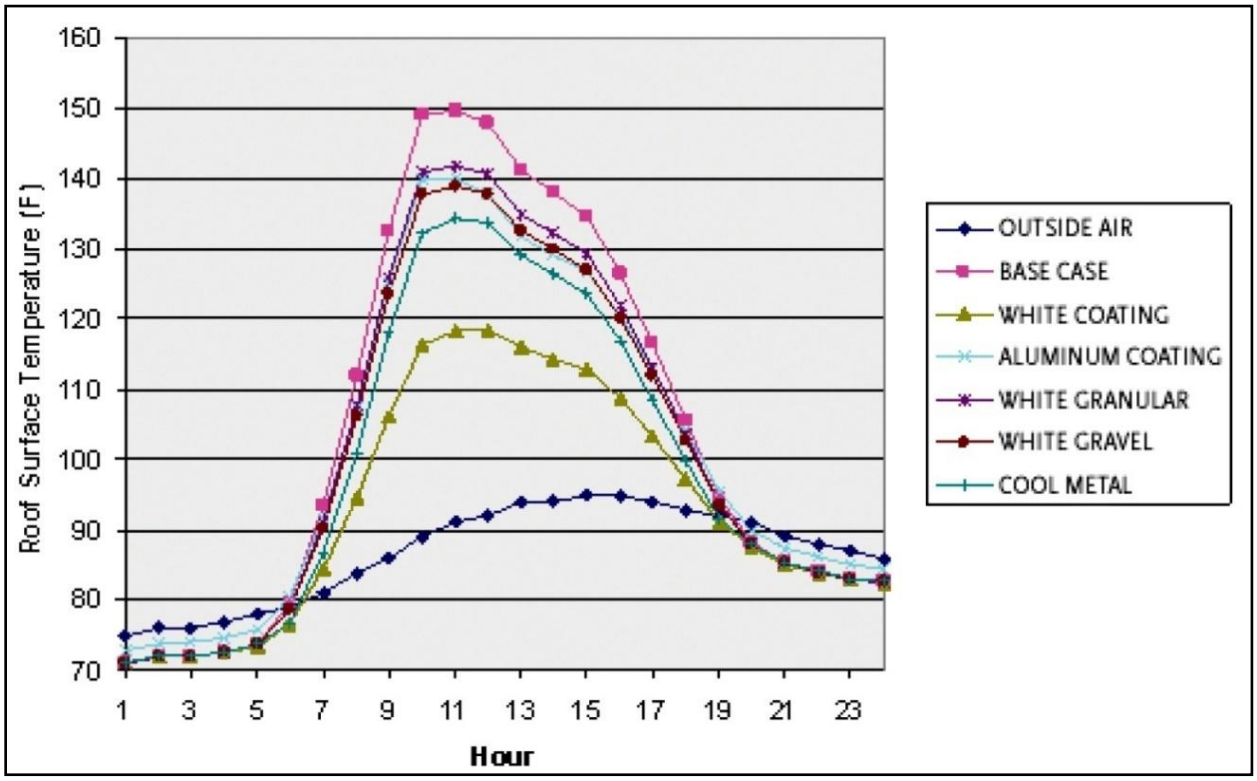
Courtesy the Cool Roof Rating Council

Another important thing happens at the surface of a roof (and when I say "surface", I mean the first layer of molecules, literally). The roof surface radiates heat (long-wave radiation) back into space at almost all times, regardless of where the sun is or what it is doing because outer space is always colder than anywhere on Earth. This is called "thermal emittance" and the extent to which it happens depends on certain characteristics of the surface material and the temperature of the surface - the higher the surface temperature, the more heat gets emitted. Thermal emittance to the sky can be reduced by high humidity, cloudiness, or even stopped altogether by thick fog. There is such a thing as the "sky temperature" which is determined by the characteristics of the atmosphere and it can be as low as -50 degrees F with extremely clear dry air at higher elevations or as high as the local air temperature when it is foggy.

Again, thermal emittance happens at night as well as during the day regardless of how cold the roof surface temperature might be. In fact, this phenomenon applies to the surface of anything exposed to the sky, thus the frost in your yard on a clear October night when the temperature drops down to around 40 degrees.

This also means thermal emittance occurs during the winter when you do not necessarily want it to, so the use of a cool roof can result in an annual energy penalty in most cooler climates, depending on how the building is being used. But then, if winter brings a thick blanket of snow, reflectivity and emissivity no longer mean anything, regardless of the roof type. Every situation is different.

A roof is considered by the US Green Building Council as "cool" if it reflects at least 70% of sunlight and has a thermal emissivity value of at least 0.9 on a scale of 0 (no emittance) to 1 (maximum emittance physically possible). Some roof surfaces, like asphalt, have very low reflectivity but very high emissivity, so even though they get super hot during mid-day, they could be even hotter; then they cool down at night much more than if they had low emissivity. Some light colored roofs reflect sunlight reasonably well, but have very low emissivity, keeping them warm at night. For maximum cooling, the trick is to come up with a material that has both high reflectivity and high emissivity, like the white materials shown in the following chart of various cool roof materials.



From the New York City DDC Cool & Green Roofing Manual

One important note on cool roofs: they tend not to stay as cool as advertised. Soon after installation, their surfaces get directly abused by rain, dirt, wind, and ultraviolet radiation from the sun, such that they typically lose 10% to 20% of their reflectivity within the first year or two. It is simply not realistic to claim a reflectivity greater than 70% for a roof that is more than two years old unless it has been cleaned on a regular basis, but it is rare to find a building owner who loves their cool roof that much.

Now for the comparison with green roofs (as if!).

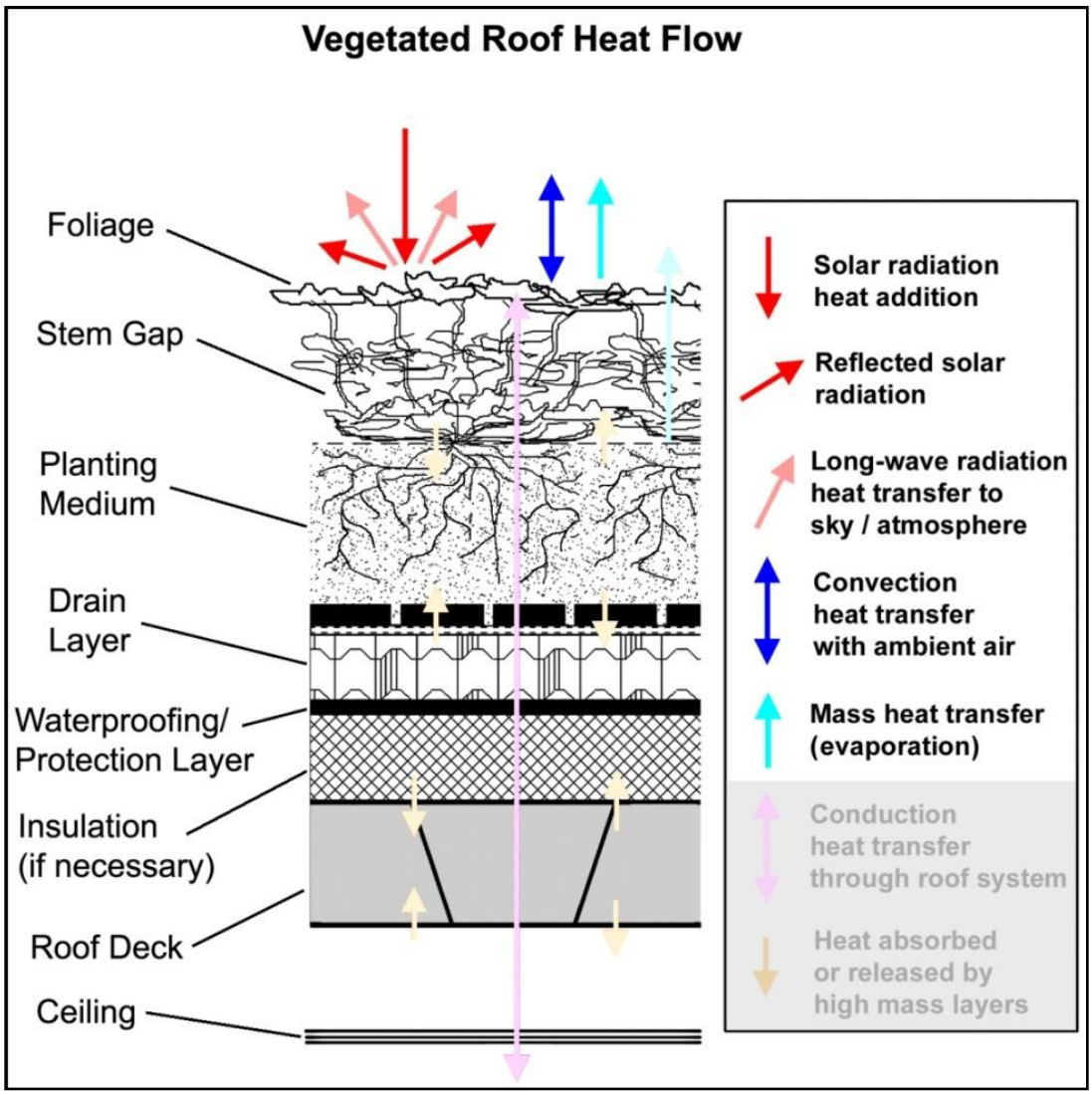
Let's face it, defining a green roof is like describing the flavor of ice cream. Tell me what kind of green roof, where it is, how it is used, what is growing on it and I can tell you something about its energy benefits and how it compares to some sort of cool roof. To keep this discussion simple, let's work with a minimalistic extensive roof in, say, Chicago - not much thermal mass but supporting foliage that provides 100% net coverage during the summer and goes quite dormant during the winter.

Cargo building at O'Hare Airport *(Xero Flor America)*

With green roofs, the outermost layer is the most crucial, such that the foliage can be thought of as its "surface" when discussing energy. Obviously, it is not a simple, smooth surface that can be described as easily as a sheet of plastic (i.e. cool roof). If our concern is the overall amount of sunlight actually reflected away from a building, we can't look at the reflectivity of individual leaves because each leaf is most likely not anywhere near horizontal. In fact, it is probably reflecting light into a neighboring leaf. The term used for the overall or aggregate solar reflectivity of a complex surface is "albedo".

A wide range of reflectivities for individual leaves can be found in vegetation, depending on the species and how much the plant is being stressed - some drought resistant plants get shinier when stressed. Other plants change leaf angle when stressed, which affects the overall albedo. For the most part, an increase in individual reflectivity translates into an increase in albedo which can range from about 0.15 (15% of light reflected away) to about 0.5 (half the light reflected away). A study by South China University of Technology measured the albedo of sedum lineare, a popular green roof plant in China, to be about 0.3. Columbia University's green roof research has measured an average daytime albedo of mixed sedums at around 0.22. Research at Penn State reports sedum albedo of 0.15. It should be noted that none of these measurements were acquired in a controlled environment while other studies of crop plants have been studied more rigorously and show higher albedo values.

Foliage also tends to have high emissivity - typically 0.80 to 0.85 for succulents, including some sedums, up to 0.99 for less drought tolerant plants. Generally, smoother, shinier leaves will have lower emissivity, but higher reflectivity. Again, these values can change depending on how much a plant gets stressed.



Copyright 2011 Christopher Wark

Yet as we have already seen, reflectivity and emissivity are only part of the story, otherwise all plants would be very shiny and fuzzy with reflectivities upwards of 95%, or a big cactus, which is built to handle high skin temperatures. Convection and evapotranspiration play an important role in always keeping foliage temperatures within 10 to 15 degrees of outdoor air temperatures, compared to the best cool roofs which often heat up to 120 degrees on a 90 degree day.

That's great for helping with the cooling, but what about winter? What happens when temperatures drop below freezing and those pulpy little sedum leaves shrivel up and go dormant? Same thing that happens with most other non-evergreen plants. For one thing, they become considerably less reflective. For another thing, their overall surface area becomes much smaller (or drops completely), so they emit less heat. Not only that, the lower branches and even some of the media get exposed to the sun. This means a green roof will absorb more radiant heat during the winter than in the summer, unlike a cool roof which always reflects the same fraction of sunlight (often resulting in a big winter energy penalty in cold climates). Then, when winter gives way to spring, exposing the media to sunlight accelerates the warming of the plants. One of nature's more clever strategies, I say.

First spring sedum rising from winter green roof litter.

One last issue that should be mentioned when comparing products is "embodied energy" - the energy required to manufacture, deliver and install a product. This is an extremely important energy topic that has been neglected so far in this series because it is not directly related to the heat transfer of a building. It is, however, relevant to an overall energy comparison of roofing systems. Why? Because a cool roof will only last a few years longer than a more conventional membrane before needing to be replaced, whereas a green roof extends the life of a membrane more-or-less indefinitely. Each time a cool roof is replaced every 20 years or so, considerable energy must be spent to get the job done, primarily in the manufacturing and delivery of the roofing material. Saving that energy is another advantage of green roofs.

Here is the rundown of a sedum-covered extensive green roof vs. a typical 3-year-old cool roof:

	Extensive Green Roof	**Average Cool Roof**
Reflectivity	summer: 0.15 - 0.5 winter: 0.1 - 0.3	summer: 0.7 winter: 0.7
Emissivity	summer: 0.8 - 0.99 winter: 0.5 - 0.7	summer: 0.95 winter: 0.95
Convection (wind cooling)	fairly significant at any wind speed	highly dependent on wind speed and roof configuration
Evapotranspiration	fairly significant, depending on water availability and temperature	none
Seasonal Adjustment	significant	none
Embodied Energy	high initially, then insignificant	Standard initially, then periodic with replacement

Throw in the myriad indirectly energy-related hydrological and environmental benefits of vegetating a rooftop and it becomes more clear why green roofs are the coolest.

Or maybe 6 episodes of this technical stuff has resulted in more confusion than clarity. Hang on for one last section when I wrap all this up in a surprisingly neat little package and decide which roofs to put it on.

7 - The Secret and How To Use It

Now that you have made an intellectual investment in six installments on the technicalities of heat transfer through a green roof, here is all that information summed up in two simple Green Roof Energy Principles:

1. Foliage uses all the heat transfer mechanisms nature makes available in order to remain within a few degrees of the ambient outside air temperature. If it can't do this, the plant goes dormant, dies, or transmogrifies into a cactus. This means that a green roof with active, healthy foliage can be assumed to remain very near the current outdoor temperature. In cooler climates, it will typically be a bit above ambient temperature when the plants are dormant. For those who may enjoy doing the energy calculations, this property of foliage means that the surface of a green roof can be accurately simulated as a nearly perfect solar reflector during summer and with fairly high emissivity (I typically use 0.9 for active vegetation and 0.7 for dormant green roofs).

2. The greater the thermal mass, the more it dampens diurnal temperature swings. This means that for an intensive green roof, the middle of the soil can be regarded as always staying close to the overall average seasonal temperature, especially if the soil can remain damp. For extensive green roofs, this effect diminishes with depth and will also depend on climate, media density and the amount of insulation under the green roof. For building energy calculations, this part requires some engineering skill, depending on one's level of interest in things like accuracy and precision.

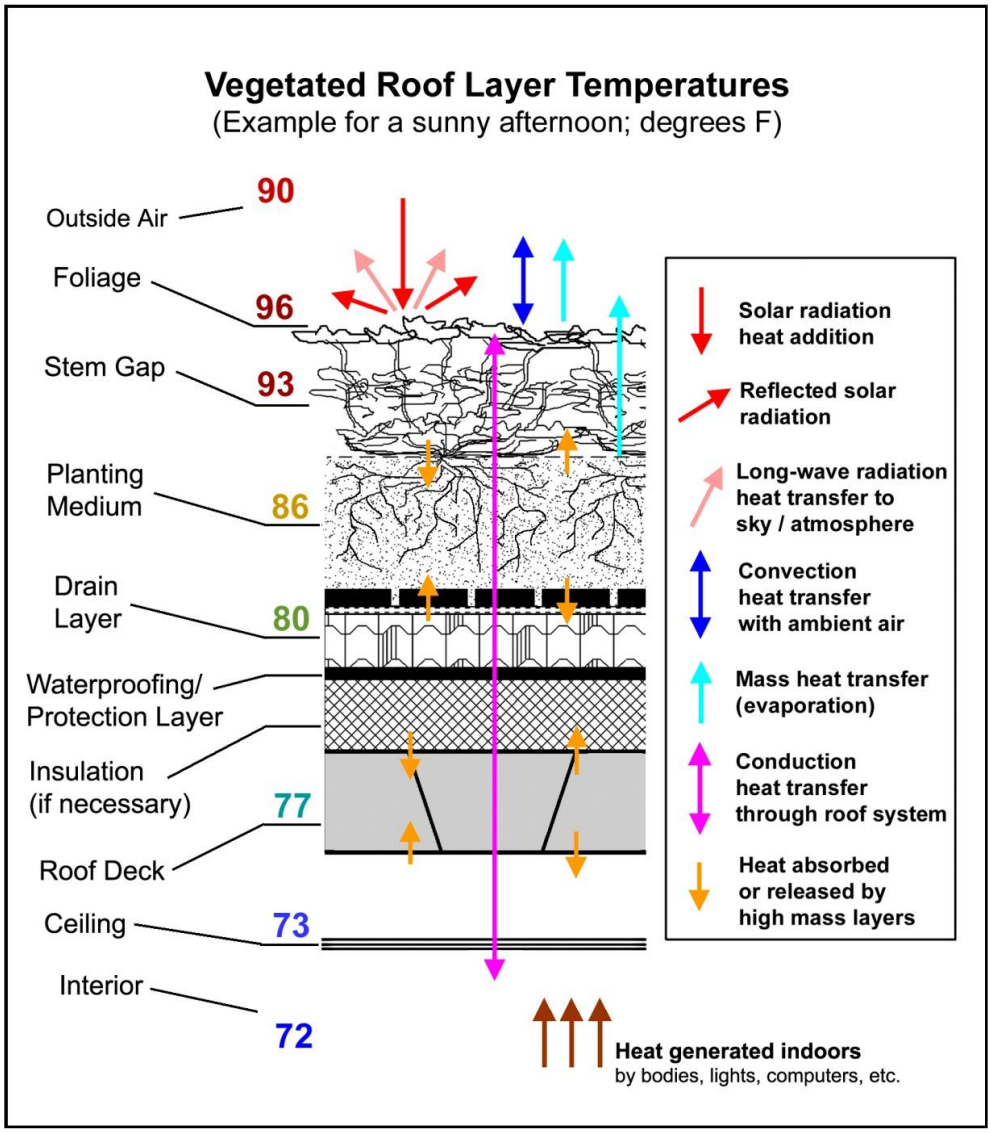
Commonly used whole-building energy calculation tools such as eQUEST and EnergyPlus can model solar reflectivity and thermal mass quite easily (although the accuracy of the thermal mass algorithm in eQUEST and other DOE-2 based programs is often questioned by engineers, including me).

We have covered some important ways in which foliage deals with all the excess solar heat energy. If plenty of water is available, most plants can stay within just a few degrees of the surrounding air temperature and many plants, like corn and cotton, can actually drop slightly below ambient temperatures when well irrigated. But when water is scarce, the leaves of most sun-loving plants are still able to stay within 10 to 15 degrees Fahrenheit through convection, reflection, and heat emission. Or in the case of cacti, the outer skin can get hotter but the interior stays cool because of thermal mass. That's five different ways of dealing with heat *as needed* (or dispensing with all five when collecting more heat is better during winter) for a total of six different thermal management tools that can be described by our two Green Roof Energy Principles.

Being clever humans who can solve almost any problem that nature throws at us, we should be able to duplicate these Energy Principles without the cost and liability of messing up a perfectly good roof with dirt, water, plants, birds, bugs, and the dreaded roof snakes. After all, we have thousands of years of experience competing with nature and transforming bits of it into tightly controlled environments for ourselves.

For the most part, building more weight into the roof structure is not a problem for a talented engineer, so now we just need to invent a cheap, maintenance-free, super-long-lasting product that can reject all solar energy during summer and absorb a little heat when it gets cold outside. So far, the closest roofing engineers have come is cool roof technology which only performs two of the five jobs needed to duplicate Principle 1. The best roofing companies can do so far (without using super reflective coatings) is to keep a roof within 25 degrees above ambient air temperature during the summer – about the same as the skin of a cactus under

extreme conditions – but typical performance is usually worse and decreases with time. This technology can also result in the roof temperature dropping below the outside air temperature during winter which hurts more than it helps in colder climates (this problem has been addressed with thermo-chromic coatings, but they are still experimental). While costing more than traditional waterproofing, a cool roof is still initially cheaper than a green roof but then requires replacement periodically, making it more expensive in the long run.



Copyright 2011 Christopher Wark

Another way to battle nature is to attempt to beat it at its own game. For several years I looked at potential roof covering strategies using bio-mimicry - copying nature's tactics for controlling heat through convection, evaporation, and emissivity. As I mentioned, cool roof material technology can already take care of radiative cooling. Evaporative coolers (cooling towers) are standard equipment in commercial air conditioning systems, even if they are configured a bit differently than what we want for mimicking plant evapotranspiration. But unfortunately, engineering a roof covering that can convect heat to the air as efficiently as foliage is a

challenge and often brings one back to something that looks like feathery grass. The real trick is to incorporate all of these technologies into a single product.

Let's say some well-funded engineers actually did come up with a roof covering with all these features. What they would have is an artificial green roof that works almost as well as a real one during the summer but probably not during the winter and only lasts for a few years because plastic and metal don't regenerate like real plants. And such a roof covering would not be cheap or absorb CO2 or support the local ecology.

"worry free" plastic roof grass (*courtesy AV Turf*)

Instead of bio-mimicry, green roofs are simply bio. They don't copy nature, they are nature. And if nature has already optimized survival strategies for us, why reinvent it? This is why a healthy green roof with nature-made components will always be way cooler than any man-made technologies. This is the beauty of working *with* nature instead of fighting it.

Naturally engineered sedum (*courtesy T+L Nursery*)

This brings us to the question of how best to take advantage of nature's own technology: a living roof covering. What kinds of building situations can make the most of a green roof? From an energy standpoint, a green roof will have its greatest impact on a large, single or two story building where solar heating is a major factor in the building's energy usage, especially if considerable heat is also generated internally. The foliage will get rid of the solar heat and the media will absorb and slowly release internal heat or excessive outdoor heat at night. Primary examples are single story office buildings, temperature controlled warehouses, big-box retail stores, and many manufacturing facilities. Homes with no attic or a poorly vented attic are also good candidates for a properly designed green roof.

Ford Rouge River Plant

The best geographic locations are moderately warm climates where there is a realistic possibility of completely eliminating roof insulation and significantly downgrading air conditioning. Areas that come to mind are:

- within a few miles of nearly all of the southern California coast
- one valley in from the coast (give or take a valley) for northern California up to Washington
- many eastern coastal regions south of New Jersey

This may look like a picky list, but the collective economies of these areas make up about 1/3 of the total U.S. economy. Ironically, these regions also have the fewest extensive green roofs in the U.S. Outside of the contiguous United States, similar types of coastal locations are equally good candidates and a few exceptional inland locations can also be found, such as southwestern China.

Less advantageous applications are buildings where there is little or no need for temperature control (e.g. unconditioned warehouses in moderate climates), structures where solar heating is not an issue (e.g. buildings that are shaded), and buildings with a small roof/envelope area ratio (e.g. skyscrapers).

The green roof atop the 38-story Helena apartment building in New York City only benefits the 38th floor. For this building's envelope, the windows have the biggest energy impact. (*credit: Jeff Goldberg/Esto*)

The reality of building design is that the only way to know how much a green roof will improve energy efficiency is to have a whole-building energy model created by someone with a thorough understanding of the technical portions of this series. Energy savings from a green roof, as with any architectural feature, can be realized in any situation, but the actual amount of savings is only found by considering the interdependence of building design, utilization, and location, which are always unique to a given project. Sales data, most green-whatever guidelines, and even some industry standards should never be considered absolute since they are for specific cases. They can be devalued by even a small change in a building envelope feature or mechanical system design, as is often demonstrated in a whole-building energy model. I know the impact of those changes well since I analyze them every week.

There you have it. All the complexities of how a green roof deals with heat wrapped up in two basic Green Roof Energy Principles. "So then," I hear you asking yourself, "what was the point of dragging us through those other six articles?" Two reasons:

1. Process. Not only do you now know the magic answer, you know how it came to be. The what and why of where I got the answers were revealed so that this conversation can continue intelligently. I look forward to having my process questioned so that we can all learn more.
2. Rigor. The green roof world is awash in bad assumptions of how heat moves through a green roof. These assumptions are usually based on uninformed intuition instead of good old fashioned rigorous methodology based on the First Law of Thermodynamics. It was important to address some of the most prevalent misconceptions with a meaningful discussion because nothing is greener than knowledge.

There are many reasons to cover a roof with plants. You can't beat the esthetics, storm water runoff control is often a favorite, and sometimes energy savings starts out at the top of the list only to end up near the bottom because of a lack of understanding on how to quantify the savings. My hope is that this series will help to keep energy toward the top of those lists for the right buildings and the right reasons.

References used in this series:

1. Incropera, Frank and DeWitt, David. Introduction to Heat Transfer. John Wiley and Sons, 1990. Classic heat transfer text with all the theory, equations and proper procedures an engineer needs to calculate conductive, convective, radiative, and mass heat transfer correctly.
2. Mills, A.F. Basic Heat and Mass Transfer. Irwin, 1995. Ditto.
3. Cengel, Yunus A. and Boles, Michael A. Thermodynamics: An Engineering Approach. McGraw Hill, 1994. Another excellent, very popular textbook - contains my favorite explanations of the laws of thermodynamics.
4. 2009 ASHRAE Handbook: Fundamentals. Most of the principles and guidelines necessary to understand the ASHRAE Standards.
5. MacAdam, Jennifer W. Structure and Function of Plants. John Wiley and Sons, 2009. Good fundamental text on how and why plants do what they do.
6. http://5e.plantphys.net Zeiger, Eduardo, and Taiz, Lincoln. Plant Physiology (Online), 5th edition. Sinauer, 2010. Good online companion to the text. Energy issues are addressed most directly in Chapter 9.
7. www.fao.org/docrep/X0490E/x0490e00.HTM Comprehensive guidelines on crop evapotranspiration from the Food and Agriculture Organization of the United Nations. Includes considerable background information, calculation methods and explanations, and world-wide climate and crop data.
8. www.cimis.water.ca.gov/cimis/infoEtoOverview.jsp Background information for the California Irrigation Management Information System (CIMIS).
9. www.dpi.qld.gov.au/26_9829.htm Good, concise overview of agricultural evapotranspiration calculations from the Australian government. Particularly handy for fans of the metric system.
10. https://courseware.e-education.psu.edu/simsphere/workbook/ch07.html This is a more advanced explanation of the details of stomatal heat transfer. Part of the SimSphere Workbook, courtesy of John A. Dutton e-Education Institute, A unit of the College of Earth and Mineral Sciences, The Pennsylvania State University © 2003.
11. www.ksre.ksu.edu/library/ageng2/MF2868.pdf Irrigation case study from Kansas.
12. www.fao.org/docrep/X0490E/x0490e06.htm#penman%20monteith%20equation This is the standard method for calculating evapotranspiration rates - more applicable to crops than green roofs, but still a reasonable and accepted basis for any evapotranspiration calculations.
13. http://en.wikipedia.org/wiki/Latent_heat Besides the generally useful overviews found at Wikipedia, its greatest value is as a portal for all the references found at the bottom of the page.
14. faculty.unlv.edu/landau/adaptations.htm Concise outline of desert plant adaptations.
15. www.eoearth.org/article/adaptations_of_desert_plants This section of the Encyclopedia of Earth has not been updated for some time but still gives some great descriptions of desert plant survival.
16. www.cwnp.org/adaptations.html Central Washington Native Plants website has some great images and provides a brief overview of plant survival methods in the arid region of central Washington state.
17. www.ornl.gov/sci/roofs+walls/research/detailed_papers/thermal/index.html This is a pretty good study of thermal mass for one type of house construction. It compares energy savings for different weight wall systems in several different climates.
18. www.buildinggreen.com/auth/article.cfm/1998/4/1/Thermal-Mass-and-R-value-Making-Sense-of-a-Confusing-Issue/

Excellent discussion on how to use the word "insulation" when talking about thermal mass, including the pretend R-values that are used to describe massive construction elements.

19. www.concretethinker.com/solutions/Thermal-Mass.aspx Naturally, folks in the concrete business are more than happy to talk about thermal mass. This page has a nice concise explanation.
20. www.nyc.gov/html/ddc/downloads/pdf/cool_green_roof_man.pdf There are quite a few green building manuals out there, including plenty of other governmental resources. Even though I am partial to this one, it should still not displace References 1 through 3.
21. www.commercialwindows.umn.edu/issues_energy1.php Although this page is for windows, it gives a great technical summary of solar radiation, reflectivity, absorptivity, and emissivity.
22. www.omega.com/literature/transactions/volume1/emissivityb.html#s1 Good emissivity chart of common non-metallic materials, many of which are used in construction. Emissivity can be difficult to grasp and comparing some of these values for familiar materials might help.

About the author

Christopher Wark has over 20 years of multidisciplinary engineering experience providing mechanical, thermodynamic, and electronics support and services to manufacturers, universities and national labs. For the past 8 years, he has focused his efforts on the development and promotion of technical solutions in architecture and construction. Chris is currently a Senior Energy Analyst for Viridian Energy & Environmental. At Viridian, he conducts whole-building energy analysis, air flow modeling, building envelope energy modeling and other specialized building physics analysis.

Before joining Viridian, Chris provided energy analysis and LEED consulting services for several companies, including subsidiaries of the Integral Group and previous to that served as Technical Sales Manager for Mentor Graphics Mechanical Analysis Division (formerly Flomerics Inc.), offering energy and air flow analysis solutions for architects and engineers.

In 2002, Chris established SHADE Consulting/Green Roof Innovations with his wife Wendy. With SHADE/GRI, Chris developed and marketed several innovative modular eco-roof systems, a roof system heat transfer and cost computer program, and conducted green roof system heat transfer analyses for 5 major cities and organizations. He continues to develop modular planting systems in partnership with Guiyang Chuangjia High-Tech Accelerator Co. LTD in Guiyang, China.

Chris has also been involved in other thermodynamic related work, including advanced engine research and fuel cell system development at Caterpillar Inc. and laser development at Lawrence Livermore National Lab and 2 private research laser development companies. He has presented at numerous conferences, has several articles published on a wide variety of engineering topics, and has had the privilege of working directly with several universities, including Stanford's Center for Integrated Facility Engineering (CIFE) program.

Chris holds Bachelor's and Master's of Science degrees in Mechanical Engineering (with a minor in Materials Science) from Washington State University. His graduate work focused on fluid dynamics and combustion.