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The Cost of Design: A Life-Cycle Assessment of Green Infrastructure Technology

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THE COST OF DESIGN:
A LIFE-CYCLE ASSESSMENT OF GREEN INFRASTRUCTURE TECHNOLOGY

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Landscape Architecture

in

The School of Landscape Architecture

by
Cheryl K. Lough
B.S., West Virginia University, 2003
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ABSTRACT

Landscape architectural research of green infrastructural practices has increased dramatically over the last decade. Due to this research, many designers are suggesting some form of green infrastructure within their projects. Much of the present-day research focuses on function and not long term impacts of individual materials. The current rate of implementation of green infrastructures might not produce a drastic impact upon the environment, but with installations being realized at an ever-increasing and larger scales, even minute elements within the construction of these structures begin to influence the overall ecological footprint produced by our designs. Designers must re-evaluate the materiality of construction and select components based on a series of conditions including the life-cycle assessment associated with specifying individual products. This paper examines the current ecological footprint of one standard green infrastructure, a green roof, and investigates what substitutions might be made to lessen the environmental impacts, over time, of green roof components.

CHAPTER 1. INTRODUCTION

Continued increases in global population compounded with the rises of affluence continue to put more demands on energy consumption and the production of materials. With a large, but non-finite resource base and ever-accumulative rises in CO^2 emissions, designers must make critical decisions concerning materials and these materials' long-term impacts on the environment (Ashby, 2013). Due to climate change, continuation at our current rate of emission will eventually contribute to our own demise (Calthorpe, 2010).

Major contributors to environmental harms are contemporary construction practices. The use of non-renewable materials is the most overwhelming factor associated with these practices ("Green Building"). Building and construction activities worldwide consume three billion tons of raw materials each year or 40 % of total global use of raw materials (Ahmed, 2012). "While being eco-efficient may indeed reduce resource consumption and pollution in the short term, it does not address the deep design flaws of contemporary industry. Rather it addresses problems instead of the source, setting goals and using practices that sustain a fundamentally flawed system" (Mcdonough et al, 2003). Using fewer materials does not eradicate the negative impacts of their initial production.

The tracing of a material's life from production to disposal is called a *life-cycle assessment* or (LCA). Minimizing the drain on resources and the release of unwanted emissions is the main goal of a LCA. A LCA must be fast and allow for exploration of alternative choices of material, use patterns, and end of life scenarios (Ashby, 2013). Following a LCA, green engineering principles can be used to evaluate material alternatives (Fig 1).

The harnessing of nature for infrastructural systems is called "green infrastructure". Green infrastructure can provide critical services for communities, protecting them against the increasingly common fluctuations in climatic occurrences such as flooding, drought, and extreme temperatures ("Green Infrastructure").

The 12 Principles of Green Engineering

Principle 1 Designers need to strive to ensure that all material and energy inputs and outputs are as inherently nonhazardous as possible.
Principle 2 It is better to prevent waste than to treat or clean up waste after it is formed.
Principle 3 Separation and purification operations should be designed to minimize energy consumption and materials use.
Principle 4 Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.
Principle 5 Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.
Principle 6 Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.
Principle 7 Targeted durability, not immortality, should be a design goal.
Principle 8 Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.
Principle 9 Material diversity in multicomponent products should be minimized to promote disassembly and value retention.
Principle 10 Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.
Principle 11 Products, processes, and systems should be designed for performance in a commercial "afterlife".
Principle 12 Material and energy inputs should be renewable rather than depleting.

Fig. 1 Source: Mcdonough et al, 2003

Green roofs are a form of green infrastructure. A green roof is a multilayered vegetated roof covering (She et al, 2010). Green (or living) roofs use vegetation to improve the performance of an ordinary roof with regard to stormwater management, energy consumption, lifespan, amenity and/or create a pleasant space in an otherwise underutilized space (Snodgrass et al, 2010). Although these benefits are substantial, a measure of the entire life cycle of each individual element must also be reviewed prior to supporting an increase in their installation (Carter et al, 2008).

CHAPTER 2. METHODOLOGY

The information contained within this paper was collected from published literature, lectures, and data produced from sustainability assessment tools such as EduPack software ("CES EduPack 2014") and Principles of Green Engineering (Mcdonough et al, 2003).

To comprehend the present body of knowledge related to green infrastructure (in particular, green roofs) and the impacts of these structures on the environment, a literature review was conducted. Existing publications targeted towards landscape architects concerning the selection of materials and their LCA are limited. *Living Systems: Innovative Materials and Technologies for Landscape Architecture* (Margolis, 2007) evaluates various green infrastructure systems, but lacks specifics concerning impacts of individual materials (King, 2008). *Materials for Sustainable Sites: A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials* (Calkins, 2009) does not tell the reader how to use the individual materials. Instead, Calkins, the author, has compiled all the available research on each individual material in an attempt to assist designers in making educated material choices (King, 2008). *Materials and the Environment: Eco-informed Material Choice* (Ashby, 2013) effectively defines and explains the life-cycle assessments of individual materials, but falls short in offering alternatives for specific systems. The use of the EduPack software ("CES EduPack 2014") in conjunction with the literature provides the user with viable substitutions. The method of entering the information concerning design extents is quite complex and perhaps too cumbersome for use by many practicing landscape architects.

Lectures recorded from Dr. John Pardue's Environmental Engineering EVEG 4154 at Louisiana State University contributed to and inspired the compilation of this paper. These lectures contained information on the fundamentals of material selection and life-cycle system analysis (Pardue, 2014).

The main instrument used to determine the life-cycle analysis and the environmental impacts of green roof's materials was CES EduPack 2014 software at Level 3 Eco Design Eco Audit ("CES EduPack 2014"). This database allows the user to explore properties, conduct analysis, and produce audits on varies materials and processes.

The Principles of Green Engineering (Mcdonough et al, 2003) offered guidelines for selecting alternatives for the individual materials of the green roof system.

CHAPTER 3. ANALYSIS

I analyzed the most popular installation method for green roofs within the United States (Miller, 2014). This method includes nine layers as shown in the graphic (Fig. 2) and is commonly called an *extensive* green roof system. Extensive green roofs are a low profile (approximately 4” of growing media) vegetated roof system and are the lightest of the three systems (including intensive and semi-intensive green roofs). The systems distributed weight is usually between 12-25 lbs./sq.ft. (“Capitol Greenroofs”).

The vegetation layer is the esthetic layer of green roofs. Many associate this layer alone as establishing the roof as environmentally friendly (Bianchini et al, 2012). The vegetation layer is intended to be aesthetically pleasing. Plants perform a service in regulating storm water runoff by retention and the evapotranspiration processes (Oberndorfer et al, 2007). Due to the harshness of environment conditions on rooftops, Crassulacean Acid Metabolism (CAM) plants are recommended. CAM plants open their leaf pores to exchange oxygen and carbon dioxide in the darkness allowing the conservation of water under drought conditions (Getter et al, 2006). Sedums meet these requirements and are plants most commonly used in extensive roof systems (Bianchini et al, 2012).

The filter layer is typically produced from a thin sheet of geotextile material and prevents the infiltration of fine particles into the layers below during the drainage process. This layer also maintains the integrity of the growing media layer above (Bianchini et al, 2012).

The drainage layers role is to provide adequate flow of water off the roof during and after a rain event. This layer allows for a portion of the stormwater to be retained above where the water is allowed to flow freely off of the roof. The drainage system is designed to ensure stormwater may be used by the vegetation for longer periods of time without oversaturation of the system. This storage promotes plant growth, avoids anaerobic soil conditions, and keeps retained water from pooling on the roof ("Drainage"). These storage layers are constructed from polyethene cups resembling the indentations in an egg carton ("Green Roof Drainage Membrane, Newton 220 Reservoir").

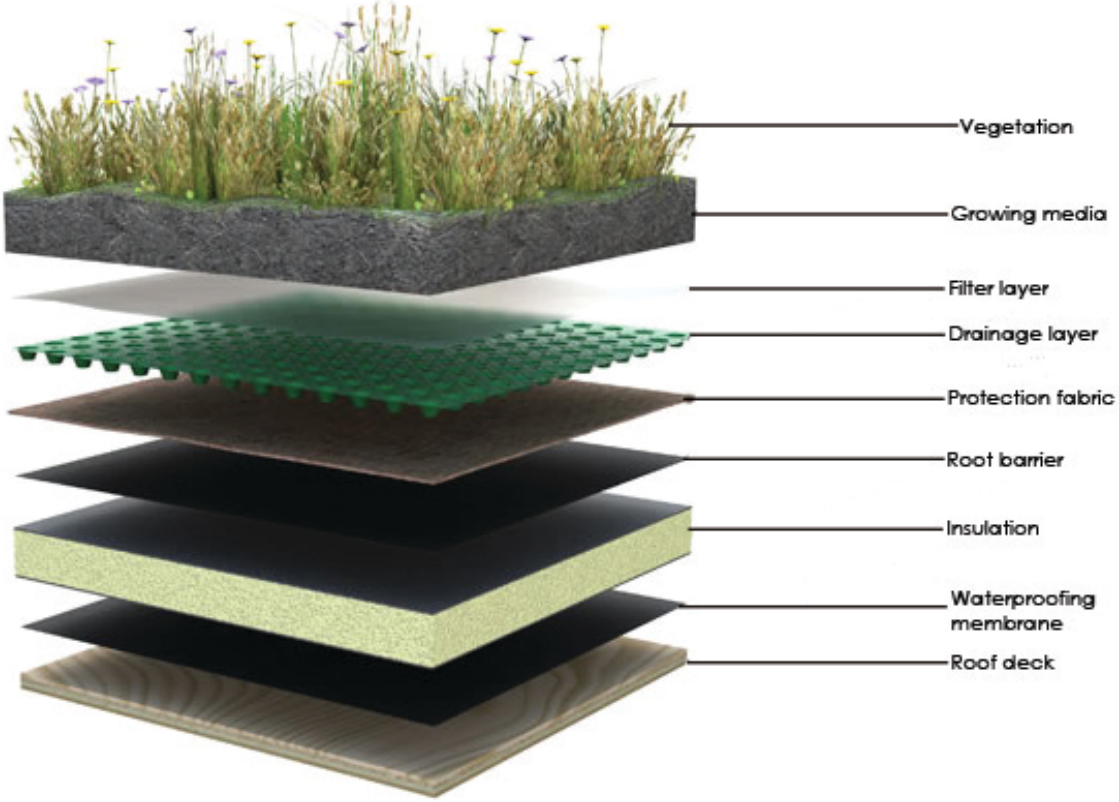


Fig. 2 Extensive Green Roof System Source: Capitol Greenroofs

Protection fabric is used to protect the waterproof membrane from damage following installation. The most common materials used are water-permeable, hard wearing and dense synthetic fibers, polyester and polypropylene ("Protection layers").

The root barrier protects the buildings' roofing assembly from roots that could penetrate into the system and cause damage. This layer usually is constructed from a polyethylene fiber.

Occasionally, a chemical additive is embedded in the fiber to prevent root growth (Bianchini et al, 2012).

The insulation layer provides thermal insulation and is rectangular sheets of extruded polystyrene. While this can be positioned below the roof deck, installation above the waterproofing layer (known as an "inverted green roof") is preferred. The inverted method adds an extra layer of protection to the waterproof membrane below ("Thermal insulation").

The waterproofing membrane is the most critical of all the layers concerning protection of the roofing assembly from water damage and/or leaks (She et al, 2010). The waterproof membrane is normally a liquid-applied membrane, a specially designed single-ply sheet membrane, or a built-up roof system consisting of three or more layers. Originally, green roofs were waterproofed with mastic asphalt, but bitumen sheets with polyester carriers and SBS modified coatings are becoming more common ("Waterproofing").

The roof deck is the structural platform that makes up the shell of the roofing system and supports all of the components of the roof barrier. Generally the roof deck is comprised of two primary forms: decking boards such as 1 x 6 or 1 x 8 and plywood ("Structural Components").

CHAPTER 4. PROCESS

The previously described components were entered into the EduPack Eco Audit software ("CES EduPack 2014") with the following base case scenerio:

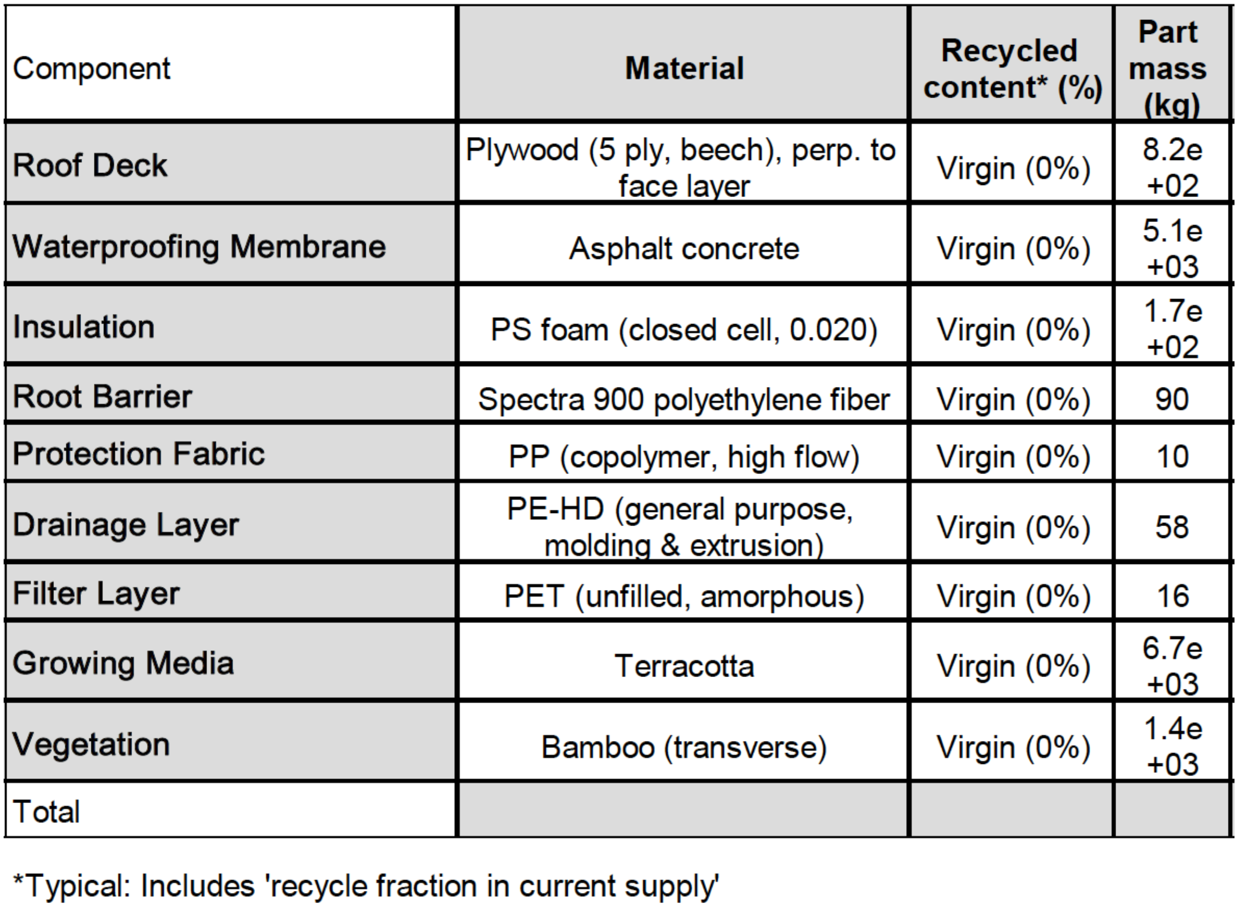
- All materials are locally sourced meaning they can be fully produced within a one hundred mile radius of the site.
- Materials will be shipped to the site via a 32 ton truck.
- The area of the green roof is equal to 92 square meters (approx. 1000 sq. ft.).
- End of life remained as *None*. This predicts that all the material will eventually end up in a landfill.
- The base case demonstrated a very extreme condition and did not include the option of recycling or the ability to source materials with recycled content.
- The useful life (or product life) of the green roof system will be 40 years.

The individual layers were entered into the software based on overall mass (Fig. 3).

Not all the materials were available as choices within the software. Alternatives were selected based on their similarities to the original material's content and mass.

Plywood was chosen to represent the roof deck. A 5 ply, beech at ½ inch thickness was elected for use as a material. This selection accurately reflects the material typically used in a green roof application.

The waterproof membrane, over the roof deck is usually applied as one of three techniques a liquid-applied membrane; a specially designed single-ply sheet membrane; or a built-up roof system consisting of three or more layers. Due to the lack of options offered within the software, I selected asphalt concrete as the waterproof membrane. Asphalt is commonly used as a waterproofing agent on roof installations. The asphalt is to be applied at a 1" thickness. The issue associated with my choice is in relation to the density of the selected material. The overall mass increases and effects the final results, but the deviation is not so extreme that the final results are severely faulted.



Component	Material	Recycled content* (%)	Part mass (kg)
Roof Deck	Plywood (5 ply, beech), perp. to face layer	Virgin (0%)	8.2e +02
Waterproofing Membrane	Asphalt concrete	Virgin (0%)	5.1e +03
Insulation	PS foam (closed cell, 0.020)	Virgin (0%)	1.7e +02
Root Barrier	Spectra 900 polyethylene fiber	Virgin (0%)	90
Protection Fabric	PP (copolymer, high flow)	Virgin (0%)	10
Drainage Layer	PE-HD (general purpose, molding & extrusion)	Virgin (0%)	58
Filter Layer	PET (unfilled, amorphous)	Virgin (0%)	16
Growing Media	Terracotta	Virgin (0%)	6.7e +03
Vegetation	Bamboo (transverse)	Virgin (0%)	1.4e +03
Total			

*Typical: Includes 'recycle fraction in current supply'

Fig. 3 Source: ("CES EduPack 2014")

The polystyrene foam selected for insulation closely matches that described by green roof suppliers ("Thermal insulation"). A 4-inch thickness was specified ("STYROFOAM™ Brand Panel Core 40 Insulation"). Variations could occur in relation to the density of this material depending on thermal requirements.

For the root barrier a polyethylene fiber 40 mil (.04 inch) unit was specified ("Choosing Root Barrier Material for a Green Roof"). Occasionally, a chemical additive is embedded in the fiber to prevent root growth, but I choose to exclude this additive as it was not an option within the auditing software.

The protection fabric, a polypropylene material, was specified as a copoly, high flow at a 5 mm thickness. It should be noted that the UV stabilized polypropylene is also a viable option.

Drainage layers vary by manufacturer, but many are similarly constructed polyethene cups. This audit considers high density PE in a 20 mil (.02 inch). The software did not supply information on the density of this material. Density information is provided by a manufacture's data sheet ("Green Roof Drainage Membrane, Newton 220 Reservoir").

Filter layers are typically a geotextile material, and a majority of green roofs use a geotextile such as PET (polyethylene terephthalate) in a 5 mm thickness. Information concerning the density was obtained from Plastic Products Inc. ("PET polyethylene Terephalate Physical Properties").

The EduPack software provides very little information concerning natural products. Terracotta in a 3-inch layer was designated to represent the growing media as many engineered green roof media mixes contain a large quantity of fired clay (Olszewski et al, 2011). The final calculation for mass was reduced by 0.5 percent (an educated guess). This reduction took into consideration the lightweight organic content of typical roof media mixes as well as the firing of the clay included within the calculation of terracotta. Additional considerations for the growing media include shell, bone, and antler (all options within the software, but all with similar densities).

The vegetation layer usually consists of a sedum mix or other shallow-rooted plant material (Bianchini et al, 2012). Bamboo in a 1-inch layer was chosen as the representative for this component from the very limited list of materials with rapidly renewable plant species as their source. Unfortunately, this is not a very viable match as bamboo must be processed, but the densities remain equivalent.

CHAPTER 5. RESULTS

The results of the audit are reflected in figures 4 and 5. Energy consumed (Fig. 4) and the CO^2 emissions emitted (Fig. 5) by the life-cycle of the materials within the green roof structure are displayed.

Upon running the EcoAudit and generating the report, several things are immediately apparent. The Material phase had both the largest energy footprint and CO_2 footprint by a significant magnitude with over 95% of both categories in the Material phase (Fig.4 and Fig. 5). The greatest impact for improving the energy and CO_2 footprints will be found in this phase, but there are possibilities for improvement in all phases of the life-cycle of the system.

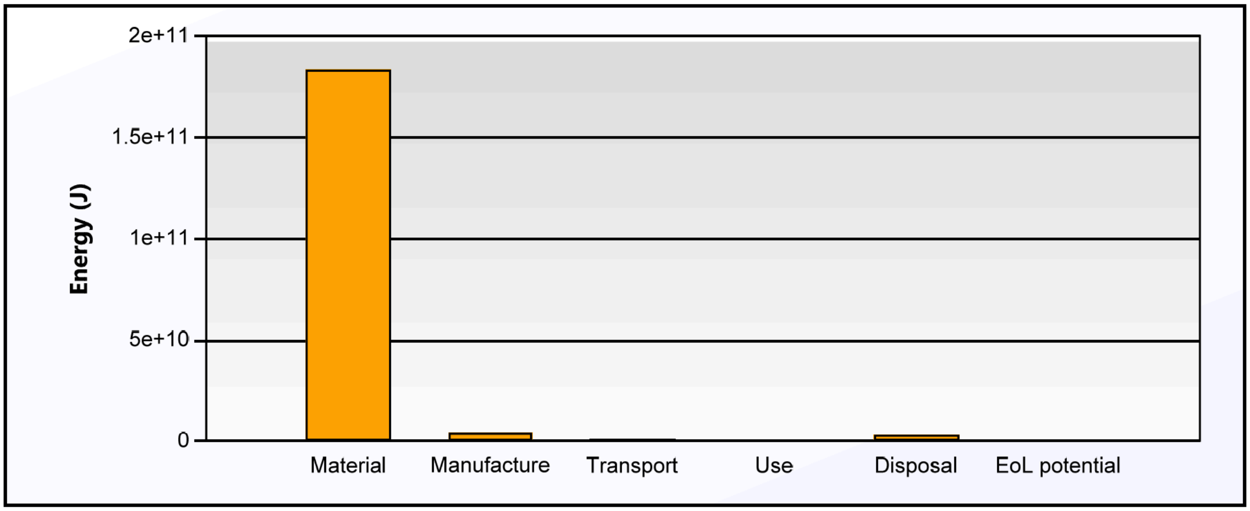


Fig. 4 Energy Footprint Summery Source: (“CES EduPack 2014”)

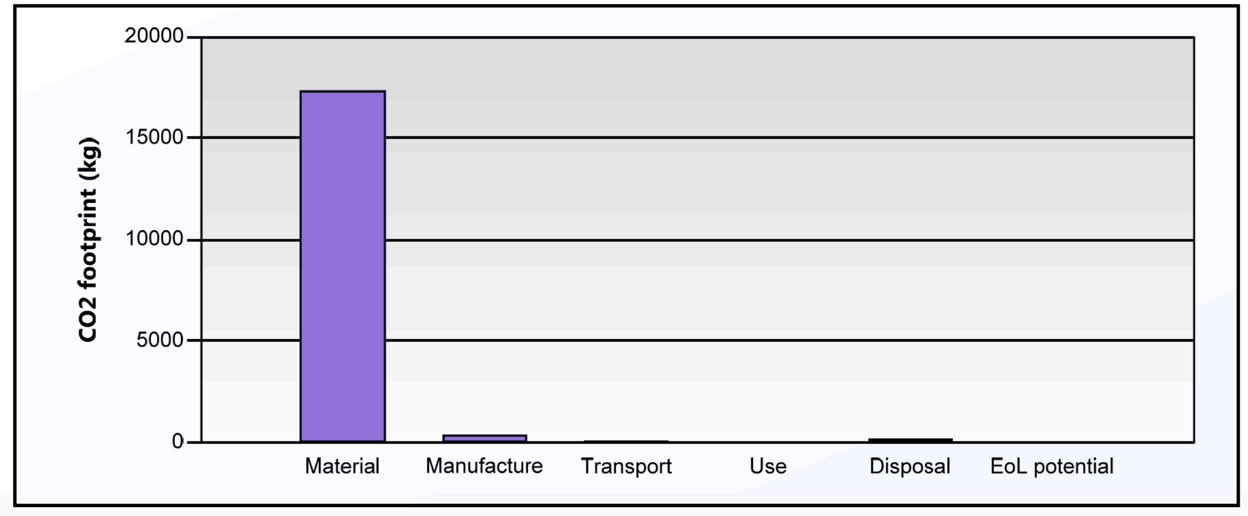


Fig. 5 CO ^{2} Footprint Summery Source: (“CES EduPack 2014”)

These results reflect Ashby’s findings in chapter 13 of his book. He argues that developed countries must increase material efficiency (providing more material services with less material production). He considers this a “precautionary principle”, meaning that the anticipation of a shortage of materials is better than a reaction to the predicted shortage (Ashby, 2013).

CHAPTER 6. OPPORTUNITIES

Research concerning viable ecologically sensitive alternatives for each of the materials listed was conducted. These “replacements” must function as well or better than the base case materials specified.

The focus of exploration for alternative materials was within three categories: alternative recycled waste materials, rapidly renewable materials, and biological engineering.

Alternative recycled waste materials assist in keeping material production levels down by reusing existing materials already in the use stream (Chloe et al, 2009). Rapidly renewable materials are plant based and typically harvested within a ten-year cycle (“NJ GREEN BUILDING MANUAL-Rapidly Renewable Resources”). Unlike petroleum-based materials that are non-renewable, rapidly renewable materials can regenerate quickly and be broken down completely and reused by natural processes ("Rapidly Renewable Materials.") Biological engineering is an emerging discipline that encompasses engineering theory and practice connected to and derived from the science of biology ("About Journal of Biological Engineering"). This new discipline’s focus on the practice of *Biomimicry* permits the creation of new products based on innovation that seeks sustainable solutions to human challenges by emulating nature’s time-tested patterns and strategies ("What Is Biomimicry?").

When assessing a green roof’s vegetation layer it is important to remember that the most significant determining factor of what plants will grow there are climate and weather. A process referred to as “green roof plant modeling” considers light and wind as the most important variables to consider when evaluating conditions for plant material (Songer, 2011). CAM plants are proven to be the most efficient and viable species for green roofs (Getter et al, 2006). Sedums (a CAM species) are the most successful plants for extensive green roofs, but are also susceptible to fungus and disease in areas with high heat and humidity. The placement of a biodiverse mix of species including both CAM and other varieties must be considered in areas prone to humid conditions (Songer, 2011). Irrigation is often installed to assist in establishment of plant species on green roofs, but it should be temporary and a time line for removal should be established during initial design.

A substitution for growing media could be a brown roof. Brown roofs are biodiverse green roofs, but their growing media is composed of recycled building materials, soil, and spoil from the surrounding site (United States). Results have shown that the alternative substrates perform as well as standard substrates and assist in keeping items such as sewage sludge and paper ash out of landfills (Fentiman, 2006). Experiments are underway to reduce the effects of heavy metal-containing nanoparticles on beneficial soil microbes. These “soil microbes” function in element cycling, pollutant degradation, and plant growth (Gajjar et al, 2009).

The following four layers (filter, drainage, protection, and root barrier) conventionally are constructed from plastics. The problem with plastics is that they do not completely disintegrate. They simply break down into smaller pieces and not into their basic components. They often are prone to absorbing other harmful chemicals and particles migrate into the surrounding environment and poison the ecosystem (Power, 2014).

One suggestion for the reduction of plastics in the materials system is reuse. There are millions of tons of manmade polymers already in circulation throughout the world with no way to break the materials’ molecules down. These immortal materials could be recaptured and turned into products and materials that take advantage of plastics (Power, 2014). The advances in optical sorting (the automated process of sorting solid products using lasers) have assisted vastly in making this process more efficient and economical (Graham, 2006).

Some researchers are combining thermoplastics with renewable resources. One such example is a combination of thermoplastics with rice husk and cotton linters (recycled cotton fibers). The resulting environmental impact, as compared to conventional virgin thermoplastics, is reduced significantly with the main reduction occurring during the materials' acquisition and processing phases. Composites obtained from renewable resources are still in an embryonic state of development when compared to petroleum-based plastics, but increased research and mass production should only escalate their efficiency (Vidal et al, 2008).

The insulation layer must perform its job of providing thermal protection to the adjacent structure below as well as additional protection to the waterproofing membrane. Natural products such as wool and recycled cotton are being investigated for their insulation properties, but one material stands out for its ability to withstand deterioration and strong resistance to varying temperature and humidity and that is cork. Cork is carbon neutral, biodegradable, light, non-permeable to gases and liquids, elastic, flame resistant, and retains excellent thermal, acoustical and vibration insulation properties ("EnviroCork Natures Natural Insulation"). Cork waste generated during the manufacturing process is ground and used to make agglomerated cork products. Cork powder that is generated by the grinding process is collected and burned to help fuel the factory ("How Cork Is Made"). The downside to the use of cork is its availability. Cork is typically harvested in and around Portugal (EnviroCork, 2009). There are currently two national recycling programs for cork ("Cork Recycling) and with their increased popularity exist a possibility for the production of cork insulation products within the United States.

The required waterproofing membrane keeps the structure below safe from the intrusion of moisture. Some believe that as long as there is a solid underlying structure and a reliable roof membrane, the remainder of the construction can be less complicated (Kiers, 2013). For a layer that is so vital to the survival of the entire system, longevity becomes the defining factor to selecting a material. Pre-engineered membranes are durable, resist chemical damage and can be installed without fumes or flames ("Green Roof Systems"). Unfortunately, these membranes are created from plastics, but recycled content could assist in reducing the environmental impact during the production phase.

The roof deck material can vary on a green roof depending on the type of structural support warranted by the building. For purposes of this paper, I have selected a wooden structure below the green roof. An alternative for the use of plywood is hemp board. A composite made from hemp (a rapidly renewable material) and lignin (a natural polymer found in all plants and trees), hemp board is strong moisture resistant substitution to the use of virgin timber for plywood production ("Hemp Board").

CHAPTER 7. CONCLUSIONS

The EduPack 2014 software has a vast library, but is limited in information concerning organic and composite materials. An extension of the software to include recently developed environmentally sensitive and organic materials would assist in producing a more accurate life-cycle cost analysis of structures and their components.

Concerning the individual components of green roofing technology, the need for more regional and practical research is immanently important (Dvorak et al, 2010). The eco audit summery confirms that regional standards for materials should be established based on climate differences and availability of materials (Olszewski et al, 2011). Reuse of materials remains the most ecological option at this time, concerning the life-cycle cost of green roofs. The reliance on the production of virgin plastics appears to weigh heavily on the audit. Keeping these items out of landfills and within the material life-cycle circle will assist greatly in alleviating a major portion of the CO2 and energy expenditures (Ashby, 2013).

Even with the analysis described above, questions remain. For instance, are all of these layers of materials even necessary to produce a successful green roof system? Has the industry in America overcomplicated the entire system in an effort to increase profits? One recent article points out that while studying green roofs in Switzerland it was noted that there were no systems, no plastic trays, no manufactured "moisture retention layers," or synthetic filter fabrics. Most consisted of a simple layering of straw, or China reed (*Miscanthus sinensis*), topped with native soil from the site (sometimes mixed with lava rock or gravel), and planted with a wildflower seed mixture (Kiers, 2013). Speculation on the success of these Swiss systems could assume that the climate is more hospitable or that residents of Switzerland prefer a different aesthetic. Even so, the Swiss approach should generate a conversation comparing the varying systems.

Continued exploration of the intended functions of green roofs is mandatory in developing systems in the future that provide benefits that are socially, economically, and environmentally appealing. This process begins when professionals and the general public realizes the extreme impacts of our consumption of products and the urgency with which we should be seeking solutions.

REFERENCES

"About Journal of Biological Engineering." *Journal of Biological Engineering*. BioMed Central Ltd, n.d. Web. 27 Jan. 2015. <http://www.jbioleng.org/about>.

Ahmed, Rehan. *Construction and the Environment*. Rep. Ministry of Works, Municipalities Affairs and Urban Planning - Kingdom of Bahrain, 25 Apr. 2012. Web. 3 Jan. 2015. <http://websrv.municipality.gov.bh/mun/docs/MunicipalConference2012/Day1_25thapril/papers/15.%20Rehan%20Ahmed.pdf>.

Ashby, M. F. *Materials and the Environment: Eco-informed Material Choice*. Amsterdam: Elsevier/Butterworth-Heinemann, 2013. Print.

Azlan, Nik Ismail. *Research Methodology in Landscape Architecture*. Singapore: Trafford On Demand Pub, 2013. Print.

Bianchini, Fabricio, and Kasun Hewage. "How “green” Are the Green Roofs? Lifecycle Analysis of Green Roof Materials." *Building and Environment* 48 (2012): 57-65. *Elsevier*. Web. 12 Jan. 2015.

Bovea, M.d., and V. Pérez-Belis. "A Taxonomy of Ecodesign Tools for Integrating Environmental Requirements into the Product Design Process." *Journal of Cleaner Production* 20.1 (2012): 61-71. Web. 14 Jan. 2015.

Brooks-Church, Gennaro. "Choosing Root Barrier Material for a Green Roof." *Eco Brooklyn Inc*. Eco Brooklyn Inc., 29 June 2009. Web. 25 Jan. 2015. <http://ecobrooklyn.com/choosing-root-barrier-material/>.

"Brown Roofs." *Rio Group Website*. Rio Group, 2011. Web. 28 Jan. 2015. <http://www.riogroup.co.uk/brown-roofs.php>.

Calkins, Meg. *Materials for Sustainable Sites: A Complete Guide to the Evaluation, Selection, and Use of Sustainable Construction Materials*. Hoboken, NJ: Wiley, 2009. Print.

Calthorpe, Peter. *Urbanism in the Age of Climate Change*. Washington, DC: Island, 2010. Print.

"Capitol Greenroofs: Green Building and Landscape Architecture in Washington DC." *Capitol Greenroofs: Green Building and Landscape Architecture in Washington DC*. Capitol Greenroofs, n.d. Web. 30 Sept. 2014. <http://www.capitolgreenroofs.com/>.

Carson, T.B., Robert Hakimdavar, K.J. Sjoblom, and P.J. Culligan. *Viability of Recycled and Waste Materials as Green Roof Substrates*. Tech. N.p.: ASCE Geo Congress, 2012. *ResearchGate*. Web. 4 Jan. 2015. <https://www.researchgate.net/publication/268512805_Viability_of_recycled_and_waste_materials_as_Green_Roof_substrates>.

Carter, Timothy, and Andrew Keeler. "Life-cycle Cost–benefit Analysis of Extensive Vegetated Roof Systems." *Journal of Environmental Management* 87.3 (2008): 350-63. *Elsevier*. Web. 12 Jan. 2015.

CES EduPack 2014. Cambridge: Granta Design Limited, 2014. Computer software.

"Choosing Root Barrier Material for a Green Roof." *Eco Brooklyn Inc*. Eco Brooklyn Inc., n.d. Web. 12 Dec. 2014. <http://ecobrooklyn.com/choosing-root-barrier-material/>.

Clark, Corrie, Peter Adriaens, and F. Brian Talbot. "Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits." *Environmental Science & Technology* 42.6 (2008): 2155-161. Web.

"Cork Recycling." *Napa Recycling*. Napa Recycling, n.d. Web. 4 Jan. 2015. <http://naparecycling.com/cork-recycling/>.

De Pauw, Ingrid C., Elvin Karana, Prabhu Kandachar, and Flora Poppelaars. "Comparing Biomimicry and Cradle to Cradle with Ecodesign: A Case Study of Student Design Projects." *Journal of Cleaner Production* 78 (2014): 174-83. *Elsevier*. 9 May 2014. Web. 15 Jan. 2015. <www.elsevier.com/locate/jclepro>.

"Drainage." *Green Roof Solutions-Products*. Green Roof Solutions, n.d. Web. 5 Jan. 2015. <http://greenroofsolutions.com/drainage.html>.

Dvorak, Bruce, and Astrid Volder. "Green Roof Vegetation for North American Ecoregions: A Literature Review." *Landscape and Urban Planning* 96.4 (2010): 197-213. Web.

"EnviroCork Natures Natural Insulation." *Cork Insulation The Only Carbon Neutral Insualtion*. Cork Insulation, 2009. Web. 29 Jan. 2015. <http://www.cork-insulation.com/>.

"FAQ's." *Greenroofs.com*. Greenroofs.com, LLC, n.d. Web. 27 Sept. 2014. <http://www.greenroofs.com/Greenroofs101/faqs.htm>.

Friedman, Daniel. "Insulation." *InspectAPedia.com - Building & Indoor Environment Problem Diagnosis & Repair*. InspectApedia.com, 2015. Web. 3 Feb. 2015. <http://inspectapedia.com/index.htm>.

Friedrich, Chuck, and Rick Buist. "THE ORGANIC QUESTION." *The Living Architecture Monitor* Winter (2008): 16-21. *The Living Architecture Monitor*. Green Roofs for Healthy Cities, 2008. Web. 10 Nov. 2014. <http://www.greenroofs.org/resources/best_practices.pdf>.

Gajjar, Priyanka, Brian Pettee, David W. Britt, Wenjie Huang, William P. Johnson, and Anne J. Anderson. "Antimicrobial Activities of Commercial Nanoparticles against an Environmental Soil Microbe, Pseudomonas Putida KT2440." *Journal of Biological Engineering* 3.1 (2009): 9. *Journal of Biological Engineering*. Web. 13 Jan. 2015.

Getter, Kristin L., and Bradley Rowe. "The Role of Extensive Green Roofs in Sustainable Development." *HortScience* 41.5 (2006): 1276-285. *Msu.edu*. Web. 3 Jan. 2015.

Graham, Bob, comp. *A Review of Optical Technology to Sort Plastics & Other Containers*. Rep. TThe Environment & Plastics Industry Council, Apr. 2006. Web. 16 Dec. 2014. <http://www.plastics.ca/_files/file.php?fileid=itemcfqyQDmpdf&filename=file_Sorting_Mixed_Plastics_Report_Apr06.pdf>.

"Green Building." *Environment and Ecology*. Environment and Ecology, n.d. Web. 10 Jan. 2015. <http://environment-ecology.com/environment-and-architecture/80-green-building.html>.

"Green Infrastructure." *Asla.org*. The American Society of Landscape Architects, n.d. Web. 4 Jan. 2015. <http://www.asla.org/greeninfrastructure.aspx>.

"Green Roof Benefits." *GRHC WEBSITE*. Green Roofs for Healthy Cities, 2014. Web. 9 Jan. 2015. <http://www.greenroofs.org/index.php/about/greenroofbenefits>.

"Green Roof Drainage Membrane, Newton 220 Reservoir." *Newton Waterproofing*. John Newton & Co Ltd, n.d. Web. 15 Oct. 2014. <http://newtonwaterproofing.co.uk/product/green-roof-drainage-membrane/newton-220-reservoir/>.

"Green Roof Systems." *FiberTite*. Seaman Corporation, n.d. Web. 10 Dec. 2014. <http://www.fibertite.com/green_roof_systems.html>.

Green Roofs -- SW. N.p.: Green Roofs -- SW, 2010. 1-9. Web. 13 Mar. 2015.

"GREEN ROOFS." *Conservation Technology*. Conservation Technology, 2008. Web. 3 Oct. 2014. <http://www.conservationtechnology.com/greenroof.html>.

Hathaway, A. M., W. F. Hunt, and G. D. Jennings. "A Field Study of Green Roof Hydrologic and Water Quality Performance." *Transactions of the ASABE* 51.1 (2008): 37-44. Web.

"Hemp Board." *Hemp Technologies Collective*. Hemp Technologies, n.d. Web. 20 Feb. 2015. <http://www.hemp-technologies.com/page15/styled-15/page86.html>.

Holden, Robert, and Jamie Liversedge. *Construction for Landscape Architecture*. London: Laurence King Pub., 2011. Print.
"How Cork Is Made." *Madehow.com*. Advameg, Inc., n.d. Web. 5 Jan. 2015. <http://www.madehow.com/Volume-5/Cork.html>.

Kiers, Haven. "Back to Nature An Alternative Approach to Planting Green Roofs." *Pacific Horticulture Society*. Pacific Horticulture Society, Oct. 2013. Web. 2 Feb. 2015. <http://www.pacifichorticulture.org/articles/back-to-nature/>.

King, Jason. "Book Review: Materials for Sustainable Sites." *Land8*. Andrew Spiering, 2 Oct. 2008. Web. 12 Dec. 2014. <http://land8.com/profiles/blogs/book-review-materials-for-sustainable-sites>.

Kosareo, Lisa, and Robert Ries. "Comparative Environmental Life Cycle Assessment of Green Roofs." *Building and Environment* 42.7 (2007): 2606-613. *Elsevier*. Web. 12 Jan. 2015.

Margolis, Liat, and Alexander Robinson. *Living Systems: Innovative Materials and Technologies for Landscape Architecture*. Basel: Birkhäuser, 2007. Print.

Mcdonough, William, Michael Braungart, Paul T. Anastas, and Julie B. Zimmerman. "Peer Reviewed: Applying the Principles of Green Engineering to Cradle-to-Cradle Design." *Environmental Science & Technology* 37.23 (2003): 434A-41A. Web. 12 Jan. 2015.

Miller, Charlie. "Extensive Vegetative Roofs." *Whole Building Design Guide*. National Institute of Building Sciences, 27 Oct. 2014. Web. 19 Dec. 2014. <http://www.wbdg.org/resources/greenroofs.php>.

Mithraratne, Nalanie. "Carbon Footprint of Green Roofs in Singapore." *In K Hoflr Et Al. (ed) Proceedings of the Sustainable Buildings - Construction Products and Technologies* (n.d.): 629-37. *Academia.edu*. Web. 19 Dec. 2014. <https://www.academia.edu/4603239/Carbon_footprint_of_green_roofs_in_Singapore_In_K_Hoflr_et_al._ed_Proceedings_of_the_Sustainable_Buildings_-_Construction_Products_and_Technologies_pp629-637>.

Molineux, Chloe J., Charles H. Fentiman, and Alan C. Gange. "Characterising Alternative Recycled Waste Materials for Use as Green Roof Growing Media in the U.K." *Ecological Engineering* 35.10 (2009): 1507-513. *Elsevier*. Web. 9 Jan. 2015.

NJ GREEN BUILDING MANUAL-Rapidly Renewable Resources. Publication. Rutgers University, 19 May 2011. Web. 3 Jan. 2015. <http://greenmanual.rutgers.edu/newcommercial/strategies/renewableresources.pdf>.

Oberndorfer, Erica, Jeremy Lundholm, Brad Bass, Reid R. Coffman, Hitesh Doshi, Nigel Dunnett, Stuart Gaffin, Manfred Köhler, Karen K. Y. Liu, and Bradley Rowe. "Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services." *BioScience* 57.10 (2007): 823. *BioOne*. Web. 5 Jan. 2015.

Olszewski, Michael Wentworth., and Courtney A. Young. "Physical and Chemical Properties of Green Roof Media and Their Effect on Plant Establishment." *JOURNAL OF ENVIRONMENTAL HORTICULTURE* 29.2 (2011): 81-86. Temple University, 14 Feb. 2011. Web. 3 Jan. 2015. <http://www.temple.edu/ambler/la-hort/research/documents/Journal_of_Environmental_Horticulture_10-34.pdf>.

Ondimu, S.n., and H. Murase. "Combining Galerkin Methods and Neural Network Analysis to Inversely Determine Thermal Conductivity of Living Green Roof Materials." *Biosystems Engineering* 96.4 (2007): 541-50. *Elsevier*. Web. 12 Jan. 2015.

Pardue, John. Environmental Engineering 4154 Sustainability Engineering. Louisiana State University, Baton Rouge, Louisiana. Nov. 2014. Lecture.

Perritano, John. "Top 5 Green Insulation Options." *HowStuffWorks*. InfoSpace LLC, n.d. Web. 3 Feb. 2015. <http://home.howstuffworks.com/home-improvement/construction/green/5-green-insulation-options.htm/printable>.

"PET (polyethylene Terephalate) Physical Properties." *Plastic Products Inc*. Plastic Products Inc., n.d. Web. 12 Dec. 2014. <http://www.plastic-products.com/part12.htm>.

Power, Matt. "Roofing with Polymers." *GreenBuilder Building A Better World*. Green Builder Media, 15 Mar. 2014. Web. 29 Jan. 2015. <http://www.greenbuildermedia.com/blog/roofing-with-polymers>.

"Protection Layers." *Growing Green Guide*. The Growing Green Guide for Melbourne, n.d. Web. 20 Dec. 2014. <http://www.growinggreenguide.org/technical-guide/construction-and-installation/green-roofs/protection-layers/>.

"Rapidly Renewable Materials." *Poplar Network*. Poplar, n.d. Web. 01 Feb. 2015. <http://www.poplarnetwork.com/topics/rapidly-renewable-materials>.

She, Nian, and Joseph Pang. "Physically Based Green Roof Model." *Journal of Hydrologic Engineering* 15.6 (2010): 458-64. *American Society of Civil Engineers*. Web. 3 Jan. 2015. <http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29HE.1943-5584.0000138>.

Sleipness, Ole Russell. "Consuming Nature: Paradoxes of “Green” Development in the Rural Southern Appalachian Mountains." *Landscape Journal* 33.1 (2014): 37-58. Web.

Snodgrass, Edmund C., and Linda McIntyre. *The Green Roof Manual: A Professional Guide to Design, Installation, and Maintenance*. Portland: Timber, 2010. Print.

Songer, Kevin. "CAM Plants for Green Roofs, Effects of Heat and of Humidity." Web log post. *Green Roofs Florida! Urban Vertical Green*. Kevin Songer, 4 Jan. 2011. Web. 3 Jan. 2015. <http://kevinsonger.blogspot.com/2011/01/cam-plants-for-green-roofs-effects-of.html>.

Songer, Kevin. "Native Plant Patterns and Historical Rainfall Trends, Predictors of Green Roof Plant Success." Weblog post. *Green Roofs Florida! Urban Vertical Green*. Kevin Songer, 20 May 2014. Web. 4 Jan. 2015. <http://kevinsonger.blogspot.com/2014/05/native-plant-patterns-and-historical.html>.

Stokols, Daniel. "Transdisciplinary Action Research in Landscape Architecture and Planning: Prospects and Challenges." *Landscape Journal* 30.1 (2011): 1-5. Print.

"Structural Components." *Waukesha Roofing Contractor*. Waukesharoofingcontractor.com, n.d. Web. 20 Oct. 2014. <http://www.waukesharoofingcontractor.com/the-roofing-system/structural/>.

"STYROFOAM™ Brand Panel Core 40 Insulation." *Dow Building Solutions*. The Dow Chemical Company, n.d. Web. 10 Dec. 2014. <http://building.dow.com/en-us/products/styrofoam-brand-panel-core-40-insulation/?sc_itemid=%7Bec72a684-5888-48e1-99fd-fe455a50222f%7D>.

"Thermal Insulation." *Growing Green Guide*. The Growing Green Guide for Melbourne, n.d. Web. 20 Dec. 2014. <http://www.growinggreenguide.org/technical-guide/construction-and-installation/green-roofs/thermal-insulation/>.

United States. EPA. Cooper's Ferry Partnership Camden, New Jersey. *2012 GREEN INFRASTRUCTURE TECHNICAL ASSISTANCE PROGRAM*. By Maureen Krudner, Tamara Mittman, Christopher Kloss, Meishka L. Mitchell, and Maurie Smith. Environmental Protection Agency, Aug. 2013. Web. 16 Nov. 2014. <http://water.epa.gov/infrastructure/greeninfrastructure/upload/Camden_GI_Handbook.pdf>.

United States. National Park Service. "Green Roof Alternatives—Technical Preservation Services, National Park Service." *National Parks Service*. U.S. Department of the Interior, n.d. Web. 28 Jan. 2015. <http://www.nps.gov/tps/sustainability/new-technology/green-roofs/alternatives.htm>.

Universidad Politécnica De Madrid. "New Model to Predict the Thermal Performance of Vegetal Façades." *New Model to Predict the Thermal Performance of Vegetal Façades*. Phys.org, 10 Dec. 2014. Web. 10 Dec. 2014. <http://phys.org/news/2014-12-thermal-vegetal-faades.html>.

Vidal, Rosario, Pilar Martínez, and Daniel Garraín. "Life Cycle Assessment of Composite Materials Made of Recycled Thermoplastics Combined with Rice Husks and Cotton Linters." *The International Journal of Life Cycle Assessment* 14.1 (2009): 73-82. *SpringerLink*. Web. 28 Jan. 2015.

Vokey, David. *A Method to Detect and Locate Roof Leaks Using Conductive Tapes*. Tech. N.p.: n.p., n.d. *National Institute of Building Sciences*. Web. 3 Jan. 2015.

"Waterproofing." *Greenroofs.com*. Greenroofs.com, LLC, n.d. Web. 28 Nov. 2014. <http://www.greenroofs.com/Greenroofs101/waterproofing.htm>.

"What Is Biological Engineering?" *Institute of Biological Engineering*. Institute of Biological Engineering, n.d. Web. 27 Jan. 2015. <http://www.ibe.org/>.

"What Is Biomimicry?" *Biomimicry Institute*. The Biomimicry Institute, n.d. Web. 10 Dec. 2014. <http://biomimicry.org/what-is-biomimicry/>.

Yang, Jun, Qian Yu, and Peng Gong. "Quantifying Air Pollution Removal by Green Roofs in Chicago." *Atmospheric Environment* 42.31 (2008): 7266-273. *Elsevier*. Web. 12 Jan. 2015.

Zimmermann, M., H.-J. Althaus, and A. Haas. "Benchmarks for Sustainable Construction A Contribution to Develop a Standard." *Energy and Buildings* 37 (2005): 1147-157. *Elsevier*. Web. 12 Jan. 2015.

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