The Future of Engineering Education
2024 Annual Conference & Exposition
Oregon Convention Center
Portland, OR . June 23 - 26, 2024
ASEE
Paper ID #43413

Green Roofs and their Carbon Footprint

Caitlyn Blaine Christian, EIT, Oklahoma State University

Caitlyn Christian, EIT is a recent graduate from the Architectural Engineering program at Oklahoma State University. She graduated with honors and with a graduate certificate in Integrative Design of Building Envelopes. She is currently working as a structural engineer at Thornton Tomasetti in Kansas City, MO. Her work focuses on steel connection design, complex geometrical structures, and construction engineering.

Prof. Christina McCoy, Oklahoma State University

Christina McCoy, SE, RA teaches Architectural Engineering at Oklahoma State University. She is both a licensed structural engineer and architect. She graduated from Oklahoma State with Bachelor's degrees in Architectural Engineering and Architecture. She received a MS in Architecture from University of Cincinnati, focusing in the history and theory of tectonics in architecture. Professor McCoy received a MCEng with a Structural emphasis from University of Kansas. Her professional experience at Thornton Tomasetti gave her experience in long span structures, high rises, and steel connection design. Professor McCoy's interests lie in the intersection of structures and architecture. Of particular interest are instances where building technology leads the cutting edge of design.

Prof. Blake Mitchell, Oklahoma State University

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Introduction

As climate changes and limiting carbon emissions have become increasingly popular topics among today's conversations, green roofs are becoming an accepted solution when designing buildings. They are a favored option to neutralize and balance a building's carbon emissions. Green roofs do this by increasing the standard roof's insulation and reducing heat and cooling loss; this results in the reduction of energy usage from the building. In the United States, commercial and residential buildings are responsible for a third of the greenhouse gas emissions alone [1]. This is a large percentage, which is why green roofs are such an up-and-coming design decision for new buildings. As the use of green roofs becomes more prevalent, an evaluation of the benefits and challenges may be something architectural engineering programs choose to incorporate into their curriculum. This paper aims to consider the particular challenge of added weight to a roof structure, with the understanding that the addition of structural material to support this load must be considered alongside operational energy benefits that a green roof provides. In addition, the research herein provides a methodological framework for evaluating the efficacy of energy-saving strategies in general, including relevant software tools and comparative analysis.

When a green roof and vegetative weight are added to the structure of a roof, it can consequently increase the structural material needed for a project. This is especially true for green roofs with plants that need deeper soil and more water than other plant types. This additional structure will increase the material needed to construct the building and affect the carbon footprint of the building, specifically the embodied carbon. Embodied carbon is derived from the construction of the building, transportation and manufacturing of materials, and the installation of products in the building. It is a calculated value that is used to understand the total carbon emission output that it takes to make a new construction happen. It is important to understand the difference between the embodied carbon emission value and the operational energy consumption associated with the building. Operational energy consumption is the energy, like electricity and gas usage, used to operate and maintain a building's functions. It's the value that is associated with the building's carbon footprint after construction has occurred. Green roofs help lower this operational energy value by increasing the thermal insulation of the roof, but the roofs also increase the maintenance and material needed for construction.

This paper will explore a case study and analyze the effects of the additional structure on the carbon footprint of the building. It will also consider the different types of green roofs' ability to reduce energy usage and increase the thermal benefits of the roof. This study specifically focuses on a typical two-story commercial building with steel as the main structural material. Obviously, different structural materials will affect the overall outcome of the benefits or consequences; however, to limit the number of variables in this case study, structural steel was the only material analyzed.

Pedagogical implications

This paper was developed as a result of student research for the Graduate Certificate of Integrative Design at Oklahoma State University. The student is the primary author, while the co-authors are the faculty advisors. The research scope was limited to the carbon footprint of steel as the structural system, but further research could include other structures.

The student research was conducted over the course of one semester, as an independent study. Faculty advisors met with the student weekly to guide the research and provide feedback. Initial meetings included defining project goals, schedule, and parameters. Later meetings focused on reviewing analysis, interpreting results, and developing a report. Since the student was in the final semester of a nine-semester program, the requisite skills to conduct the study, including structural evaluation, carbon footprint analysis, and energy modeling had already been acquired in prior courses.

In a broad sense, this paper outlines the skills and steps that could be required to evaluate a specific sustainable design strategy in an Architectural Engineering program. Figure 1 illustrates the steps involved in this study, wherein the research team examined one bay of a building as a means to study the impact of a sustainable strategy within that bay, with the understanding that results could be measured against a baseline on a percentage basis to assess the impact on an entire building. Although green roofs were the topic of this study, the framework of evaluation could be applied to a number of additional topics wherein project design parameters are affected by design decisions that improve operational energy.

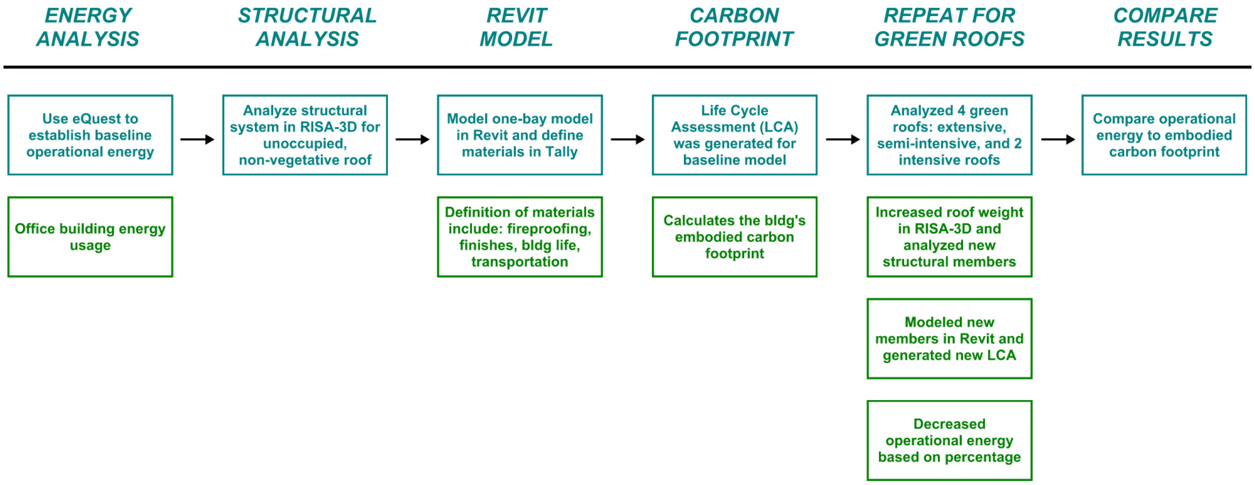


Figure 1: Evaluation steps of this study, source: author

Precedents – Basel, Switzerland

Green roofs can have many beneficial aspects regarding architecture and urban design. Green roofs are a wonderful and successful way to promote biodiversity within a city, mitigate stormwater, and reduce the effects of urban heat islands. In addition, they can increase the longevity of the roof by protecting its surface from UV damage.[2] All these perks make green roofs a great decision for the overall impact they will have on a city and the immediate environment of the building. This is the reason that many designers, developers, and building owners are choosing to incorporate green roofs.

In Basel, Switzerland, the local government decided to create incentive programs so that designers would begin to utilize green roofs into their designs. In 2002, the city government passed legislation that would subject all new and renovated flat roofs to have a green roof atop the building. This local decision has set a precedent all around the world that governments can create change in the culture surrounding architecture in hopes that this will decrease the greenhouse gases emitted from buildings.

Because of this monumental legislation, Basel is now the city with "the largest area of green roofs per capita in the world."[3] It is estimated that about forty percent of the flat roofs in Basel are green due to the construction of roughly one hundred green roofs per year.[3] As a result, the buildings have experienced an indoor temperature difference of up to five degrees Celsius, which is nine degrees Fahrenheit.[3] The amazing temperature difference has allowed for the operation energy usage to cool and heat buildings to go way down. This is a great example of how green roofs are a major benefit to reducing operational energy.

However, very little research exists that examines the additional structural material needed to support the weight and how that will impact the upfront carbon footprint of the building. This additional data impacts the overall net carbon usage of a building, and thus understanding this initial investment can give a full picture of a project's environmental impact.

Precedents – Chicago Science Center

Another example of successful green roofs is the Chicago Science Center. The botanists and researchers at the Chicago Science Center have been analyzing which types of plants thrive on top of buildings and help promote diversity within the environment. This amazing and intense research will help landscape architects and other designers choose which plants are the most beneficial to place within their green roofs. The researchers at the Science Center have stated that plants that can tolerate heat and cold will do much better than others. Plants that also do well can resist disease and display robust habits to thrive in a rooftop environment.[4] One of the scientists on this project stated that the success of a green roof is only as successful as the plants that grow on the roof.[4] Knowing this, designers can make their green roofs more economical and sustainable by choosing native plants that can handle the weather, promote biodiversity, and increase the insulation of roofs.

The Chicago Science Center not only did research on the best type of plants to grow in a rooftop environment, but the botanists also analyzed roofs with different depths of soil and vegetative media. This is a good start to giving designers more information about green roofs since most reports and analyses do not usually consider the different soil depths.

The U.S. General Services Administration released an in-depth report on the challenges and benefits green roofs provide. However, the scope of the report was limited to one depth and type of green roof within their analysis. [5]

Despite the increasing popularity of green roofs and the growing amount of research on their use, uncertainty remains on how to quantify their benefits regarding reduction of the heating and cooling load of a building. There are several factors involved in this evaluation. Firstly, climate conditions of different regions vary, varying the response of the green roof and the selection of plant life, which may have different thermal properties. Secondly, part of the thermal benefit of a green roof lies in its ability to perform as a thermal mass, slowing the heat gain or loss within a building.[6] This is clearly a bigger benefit in regions that undergo large swings in temperature in a short amount of time. Finally, water content within the soil is another variable that is hard to quantify over an annual period. The more water in the soil media the harder it is for the green roof to slow heat gain or loss due to water's ability to act as a heat conductor.[6] If the building is constructed in a climate with high rainfall or designed with plants that need a significant amount of water, this could vary the energy results greatly. Studies have attempted to condense these variables, but with different results. For instance, the American Society of Landscape Architects found a 25 % benefit,[9] while the aforementioned GSA study found only a 1% reduction in annual energy use due to heating a cooling.[5] Another contradictory statistic is cited in Green Roofs for Healthy Cities and states that a case study in Canada saw a 75% energy benefit. [8] Despite this discrepancy, proponents of green roofs argue the benefits such as the reduction of urban heat islands and storm runoff reduction are enough justification to implement green roofs in more building structures. The following case study will begin to touch on how the different varieties of green roofs can impact the carbon emissions of a commercial building.

Different types of green roofs

The precedents show how green roofs begin to neutralize a building's carbon emissions from its operational energy usage and the other benefits green roofs can provide. However, the thermal benefits, type of plants, and biodiversity are all dependent on the type of green roof that is being used. There are three different types of vegetative roofs: extensive, semi-intensive, and intensive. As expected, each of these roofs comes with a different type of loading, separate structural needs and requirements, varying maintenance needs, and a distinct type of plants. An additional type of roof that this case study will analyze is green roofs with small trees. This specific case is technically an intensive roof but has been pulled from that category to accommodate for the extra weight associated with trees and their maintenance.

Extensive green roofs are the simplest of the types of green roofs. They are also the most popular type of green roof due to their low maintenance and self-sustaining vegetation.1 The types of plants are usually succulents, mosses, grasses, or native plants. Since these plants and roofs are designed to be low maintenance, the type of plant needs to be robust and able to handle tough weather, like harsh winters and tough droughts. The main purpose of this roof is to improve the building's energy costs, mitigate stormwater, and reduce urban heat island effects; however, it is also usually designed to help with stormwater run-off. From a structural standpoint, these roofs yield a minimal increase in weight and thus create only an incremental impact in their structural support.

Figure 2: Example of an extensive green roof

Semi-intensive roofs, in comparison to extensive roofs, hold more soil, about 4 – 6 inches, and are a more enhanced version. They still usually have native plants growing atop the building but require a moderate amount of maintenance [9]. Semi-intensive green roofs (also known as simple intensive) also require more irrigation and therefore increase the weight of the system. These roofs have a larger impact on the operational energy usage of the building due to the increase in soil depth, which helps create a thermal mass that will slow the heat gain and loss.

Figure 3: Sunnyland Cove is an example of a semi-intensive green roof

Intensive green roofs need the most maintenance out of the three types, especially if there is a grass lawn. Intensive roofs are typically not one plant type; the designer could choose from simple grasses to flowers to bushes. However, they are defined as intensive due to their high maintenance. As one would expect, these roofs are the heaviest due to the need for irrigation and deeper soil. On the other hand, intensive green roofs also have the highest reduction of energy usage. They can range from 8 to 30 inches of soil depth to accommodate the large plants growing atop the structure.1 In this case study, 8 inches of soil is considered for the intensive roof and then 12 inches is considered for an intensive roof with small trees. An example of an intensive roof with small trees would be the 510 West 22nd Street project in New York City.

Figure 4: 510 W 22nd Street, New York is an example of an intensive green roof

The process and tools

The case study that follows looks at the four types of green roofs discussed and evaluates their environmental impact, both from the standpoint of embodied carbon, which is measured throughout the life of a building. A typical two-story commercial building with no vegetative roof material was designed to establish a baseline. The climatic factors are those of Edmond, Oklahoma, which has a temperate climate and can accommodate a variety of plant life. The study models one bay using various design tools as a means to determine energy usage, structural demands, and embodied carbon.

To establish the baseline carbon footprint for this building, several tools were used. One of these tools utilized is eQuest; a software that measures a building's operational energy usage, which includes the annual electricity and natural gas usage. The program derives a building's location's weather data to allow for accurate results. From there, it uses the U-values (thermal transmittance value) of the walls and roof from user input construction data to account for the thermal loss and gain within the building for an entire year. From this software program, a baseline annual electricity and natural gas usage was established.

Tally is used with Revit as a plug-in to evaluate the embodied carbon associated with a building design by creating a Life Cycle Assessment, or LCA. Once a designer models the complete design in his or her Revit file, Tally can then use the models and additional inputs to calculate the LCA. In order to ensure accuracy, the user must define every material that has been modeled in Revit. For example, the user must define a structural steel column's steel type, how it will be fire protected, and if it will be painted and the type of paint used. The LCA that Tally can provide includes the carbon emissions from the transportation of materials, construction process, and the end-of-life demolition of the building as well [10]. All these variables are customizable as they are inputted by the user. To allow for the LCA to be more thorough and complete, the operational energy values calculated from eQuest were accounted for in the report.

RISA-3D is a structural analysis software that helps the engineer design member sizes from use-input structural loads. It models member behavior and can be programmed to select the most economical member sizes based on structural loading such as gravity and wind. For this case study, structural parameters were established using typical steel strengths for United States manufacturing according to the American Institute of Steel Construction (AISC), and loads were calculated according to the American Society of Civil Engineers (ASCE) document 7-22. After the structural steel members were designed in RISA-3D, they were modeled in Revit, which allowed Tally to account for the structural material in the LCA.

All these tools were used to combine outputs and values so that a baseline model could be established for comparison to models with the four different types of green roofs. The baseline model allows for a fair comparison between all the different models so that the most unbiased and accurate results can be found. Once the baseline was established, we were able to begin designing and inputting the values for the green roofs. This case study focuses on a light, standard, deep, and max (a soil depth for small trees) green roof type.

Findings – the baseline

The first step to establishing a baseline was to use eQuest to determine the annual operational energy usage. The U-values from the wall and roof are 0.063 Btu/h -ft^2 -F and 0.036 Btu/h -ft^2 -F respectively. To put the values into perspective, the IECC 2021 code requires exterior walls above grade to have a max U-value of 0.064 Btu/h -ft^2 -F and roofs to have a max U-value of 0.039 Btu/h -ft^2 -F. After modeling a simple one-bay model in eQuest, the annual electricity usage was gathered for this building at 6445 kWh. The annual net natural gas usage was 147 kWh for heating. Once the green roofs are accounted for in the eQuest model, these usage values are expected to reduce due to the thermal benefits green roofs provide.

The second step is to gather an accurate structural system and member sizes from RISA-3D. As stated previously, this software program has the loading from a standard commercial roof modeled and then allows for the user to design the correct structural member sizes. For the baseline model, a dead load of 34 lb/ft^2 and a live load of 20 lb/ft^2 was modeled onto the roof. The dead load value was calculated from the roof's material and how much each layer weighs. The live load is the standard unoccupied roof live load value from the ASCE 7-16.

The third step for the baseline model was to accurately model a one-bay model in Revit and to define the materials in Tally. This included modeling each layer of the wall and roof sections, accurate structural member sizes, exterior cladding materials, and the foundation system. It is important to note that this case study did not define any finishes in the building, like paint or floor finishes, or change the distances to transport the materials to the construction site. Both factors would most likely add to the overall embodied carbon footprint of the building. Another factor that is important is that the building life was set to sixty years, which is what the software sets as a default for a standard life for a building in the United States. After the Tally variables were set, the operational energy values from eQuest could be inputted as well.

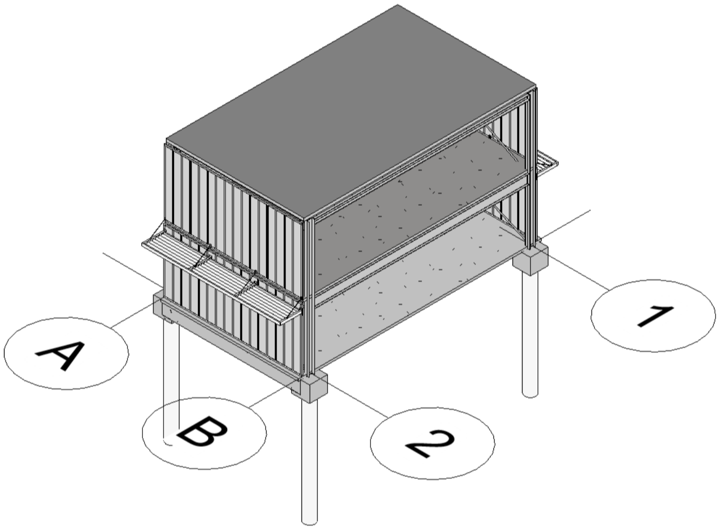


Figure 5: Baseline model in Revit

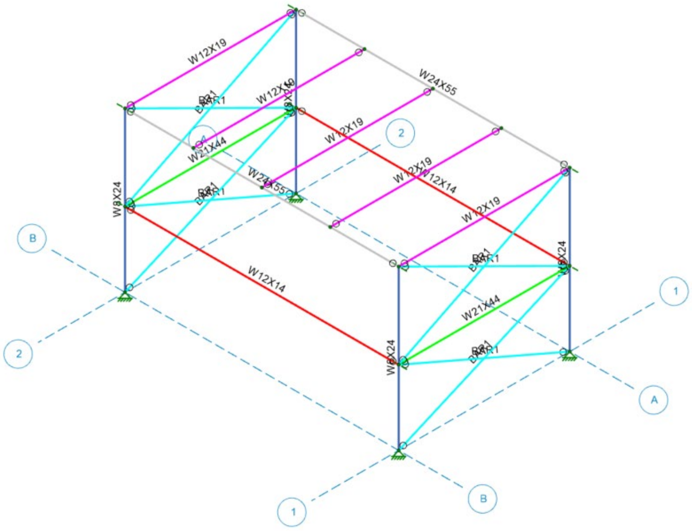


Figure 6: Baseline model in RISA

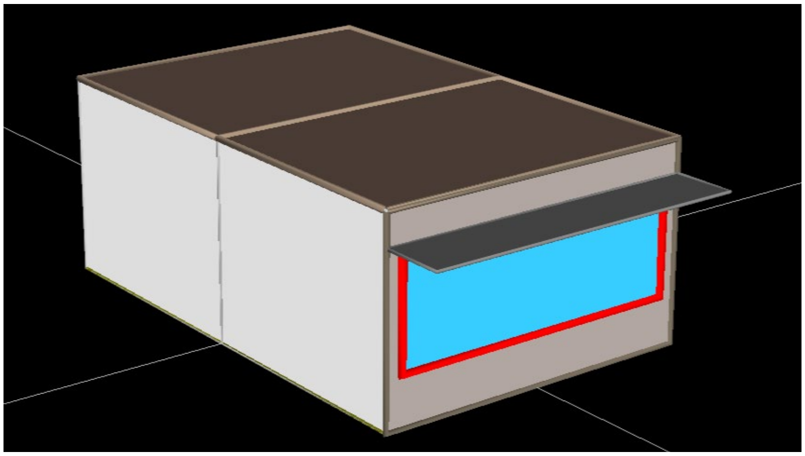


Figure 7: Baseline model in EQuest

Once these steps were completed, a Life Cycle Assessment report that contained information about the carbon footprint and the operational carbon emissions was created using Tally. First, the categories of Tally are divided into Life Cycle Stages of the building. These stages include product, construction, use (which included operational energy), end-of-life, and module D. Each stage has certain factors that contribute to its own global warming potential, or GWP. So, the lower the GWP, the better the building is from the perspective of carbon usage. The product stage factors in the extraction of building materials, transportation to a factory of materials, and the manufacturing process. The construction of the building considers the transportation of materials to the building site and the installation of building products. The GWP from the use of the building is contributed by the maintenance and repair, replacement, refurbishment, and operational energy of the building. When the structure has come to the end of its useful life, factors like demolition, transportation to a disposal site, waste processing, and disposal further add to the GWP. Module D is the 'final' stage of the building. Tally considers possible sustainable efforts like reuse, recycle, and energy recovery as a way to create a negative global warming potential and offset the building's carbon emissions.

The research findings from the Life Cycle Assessment report a baseline global warming potential (please see definition on page 13) of 415,064.97 kgCO_2eq. The product of the building accounts for forty-one percent of the global warming potential. In comparison, the operational energy comprises thirty-five percent of the baseline GWP. When the product's GWP is broken down to the basic components, the hot-rolled steel structural material has GWP of 69,775.12 kgCO_2eq; this is twenty-nine percent of the product's GWP, which is twelve percent of the total GWP. This can be expected as the building's main structural material is hot-rolled steel. However, the operational electricity is the largest contributor to the building's GWP with 201,084.00 kgCO_2eq.

It is important to note that this report was calculated with the entire production, construction, usage, and demolition in mind. This type of analysis is called "cradle to grave." This is a key feature of this assessment to keep in mind because the analysis will account for reuse potential within the materials. Reuse of materials can include energy recovery or recycling of products;

this can produce a negative GWP and reduce the building's total GWP. In this case study, Tally has calculated a negative GWP from the possibility of reuse of 170,045.94 kgCO_2eq. If this number was not taken into consideration in this report, the building's total GWP would then be 585,110.91 kgCO_2eq.

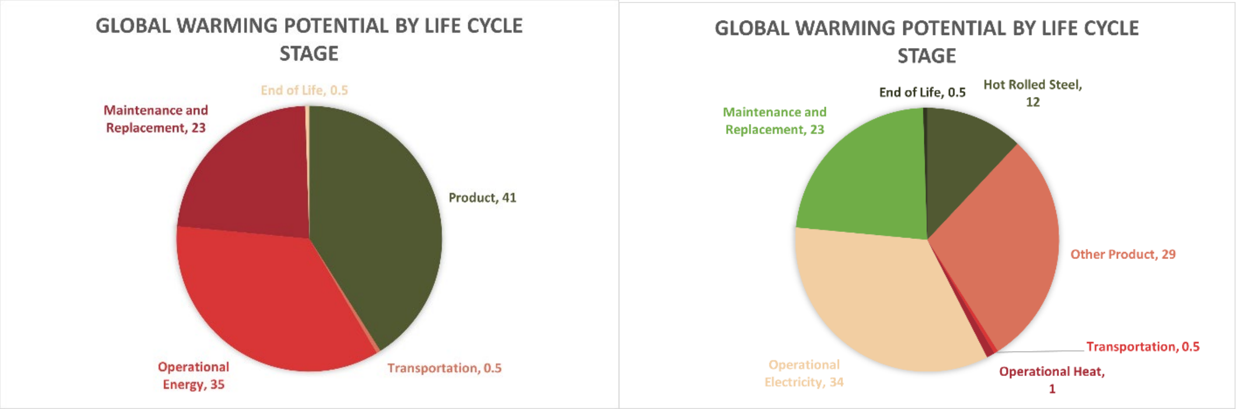


Figure 8: Global Warming Potential of Baseline, by Life Cycle Stage

Findings – extensive green roof

Once the baseline has been established, a Life Cycle Assessment for each of the green roofs can be performed. Firstly, the variables for the extensive green roof need to be set in place. One of the most important variables for the green roof is the operational energy usage. When beginning this case study, eQuest was used to calculate the annual electricity and natural gas usage with green roofs. To do this, a new U-value needed to be calculated for the roof. However, R- and U-values are not typically assigned to green roofs due to the fluctuation in water content in the roofing materials. The materials could have a thermal resistance value "assigned to the materials at fully dry, fully wet, or at some point in between." [11] Since eQuest calculates electricity and natural gas usage annually and the saturation of the green roof varies within this time period, this study opted to not assign an R-value for the green roof.

Because of difficulties with the thermal resistance values associated with soil and vegetation, this study uses a reduced percentage of the baseline operational energy, instead of an assigned green roof R-value, to simulate the reduction of the annual usage for each roof type. As discussed in the review of precedents, the community of researchers and designers who have worked with green roofs differ greatly in their conclusions about the contribution the vegetative roofs have on energy savings. Because of this variation of numbers based on many complex factors, the case study selected constants to move forward and focus on the embodied carbon increase from the additional roof weight.

The extensive green roof's variables are listed below:

- Soil Depth is 2.5 inches
- Dead Load = 34 psf (original dead load) + 20 psf (saturated green roof material) = 54 psf
- Annual Energy Savings Percentage: 1%
    - Electricity = 6480 kWh

   - Natural Gas = 145 kWh

The loading was placed in RISA-3D and new members were chosen to accommodate the new roof loading. The roof beams went from a W12x19 to a W12x22, and the roof girders went from a W24x55 to a W14x99. These structural steel members were modeled into the Revit model and the new annual operational energy values were inputted into Tally.

The Life Cycle Assessment for the steel building with an extensive green roof reported a total global warming potential of 414,815.35 kgCO_2eq. The operational energy accounts for thirty-four percent of the total GWP and the product of the building still accounts for forty-one percent. There was a little bit of an increase in the amount of hot rolled steel; for the extensive roof, the GWP is 71,851.51 kgCO_2eq. This is only a 2.9% increase in steel material from the baseline model. In comparison, the annual energy used decreased by one percent.

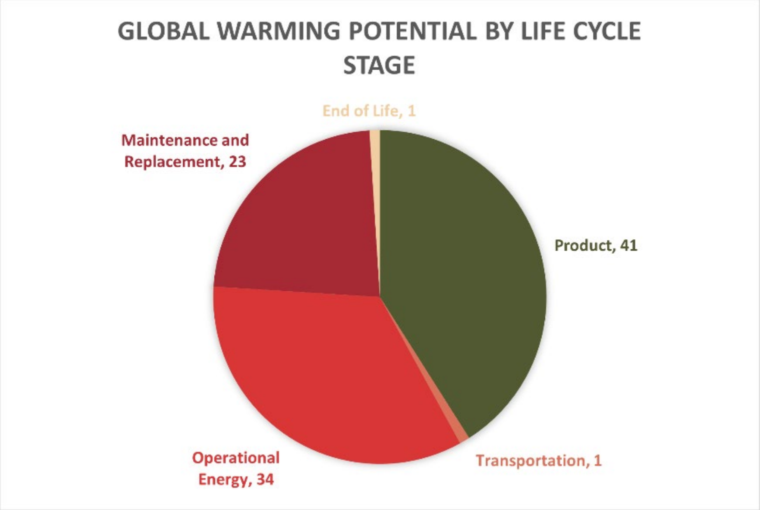


Figure 9: Global Warming Potential by Life Cycle Stage, extensive roof

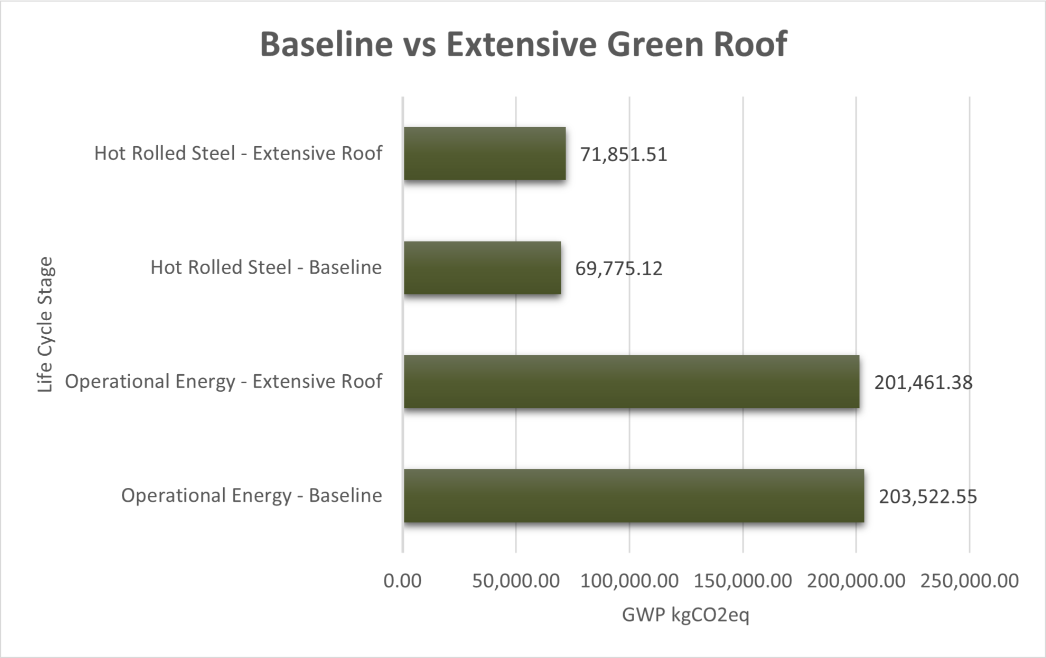


Figure 10: Global Warming Potential of Hot Rolled Steel and Operational Energy Comparison, extensive green roof vs. baseline

The findings – semi-intensive green roof

The semi-intensive roof followed the same methodology as the baseline model and the model with an extensive green roof.

The semi-intensive green roof's variables are listed below:

- Soil Depth is 4.25 inches
- Dead Load = 34 psf (original dead load) + 30 psf (saturated green roof material) = 64 psf
- Annual Energy Savings Percentage: 5%
    - Electricity = 6123 kWh
    - Natural Gas = 140 kWh

The total GWP from the Life Cycle Assessment is 409,172.05 kgCO_2eq; this is a two percent decrease in GWP when compared to the baseline model. There was an increase in hot rolled steel, which is expected due to the structural roof members. The beams for the roof are W14x22's and the girders are W24x68's. The GWP from the steel is 70,791.26 kgCO_2eq. An important feature to understand about the Tally report is that it does consider the fireproofing method and paint that will be used for the structural members. So as the members increase in size, their surface area increases, and the need for more fireproofing elements and paint increases as well. It becomes a domino effect. We can see that within the report fireproofing materials and paint had a GWP of 3354.49 kgCO_2eq in the baseline report, while the model with a semi-intensive roof had a GWP of 6864.14 kgCO_2eq. Both factors will add to the Product's contribution to the global warming potential and the embodied carbon footprint of the building.

Another important feature that is absent from Tally's Life Cycle Assessment is the ability to account for the offset of carbon emissions that the vegetation and plants can achieve by their ability to produce oxygen. This value is something that is very difficult to quantify as each green roof will vary in volume of oxygen produced due to the different plant types, amount of vegetation, and even the effects of the climate on the plants. This offset would produce a negative GWP and help reduce the overall carbon footprint of the building throughout its lifetime.

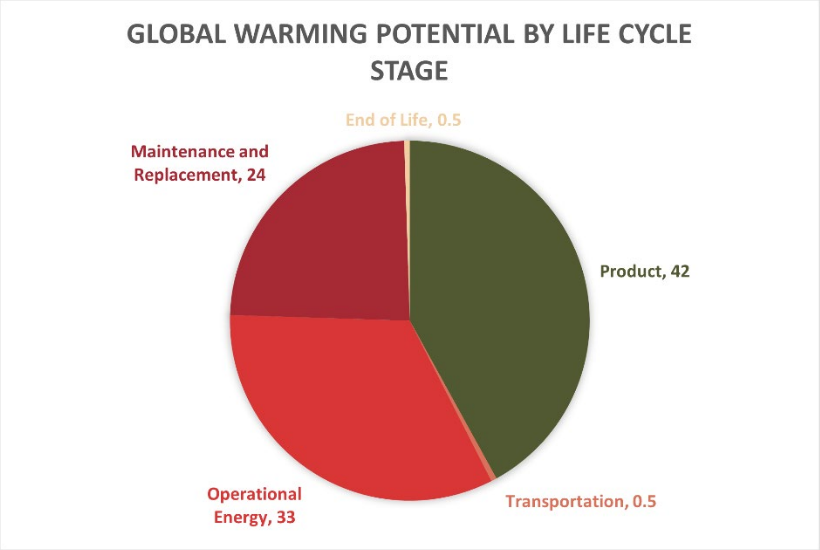


Figure 11: Global Warming Potential by Life Cycle Stage, semi-intensive green roof

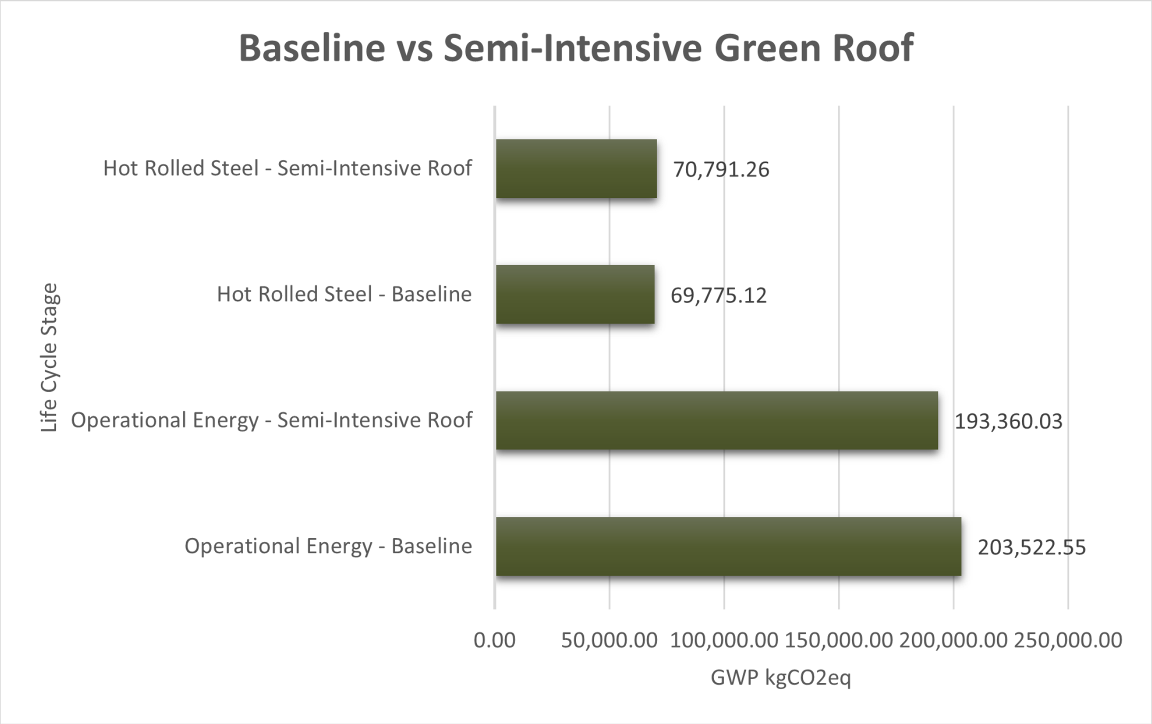


Figure 12: Global Warming Potential of Hot Rolled Steel and Operational Energy Comparison, semi-extensive green roof vs. baseline

The findings – intensive green roof

Intensive green roofs are one of the heavier green roofs and because of this, there is a large increase in saturated weight and energy savings. These values are based on the type of roof and are referenced from LiveRoof Green Modules [12]. They are a company that focuses on manufacturing and constructing green roofs for rooftop environments. The intensive roof values are below:

- Soil Depth is 6 inches
- Dead Load = 34 psf (original dead load) + 50 psf (saturated green roof material) = 84 psf
- Annual Energy Savings Percentage: 15%
    - Electricity = 5479 kWh
    - Natural Gas = 125 kWh

The building's product contributes forty-three percent to the total global warming potential, while the operational energy has been reduced to thirty-one percent of the building's total GWP. Meanwhile, the building's total GWP has been reduced to 386,341.88 kgCO_2eq; that equates to an overall 6.9% reduction. In this LCA report, the operational energy is no longer the largest contributor to the GWP when compared to the other materials in the building. The metals division (which includes hot rolled steel, steel decking, and fireproofing elements for metals) has overtaken the operational electricity with a GWP of 183,482.38 kgCO_2eq. However, the hot rolled steel did not have as much of an increase with this green roof as others. From the semi-intensive to the intensive roof, the GWP increased by 870.8 kgCO_2eq. When compared to the baseline model's hot rolled steel GWP, that is only a 2.6% increase.

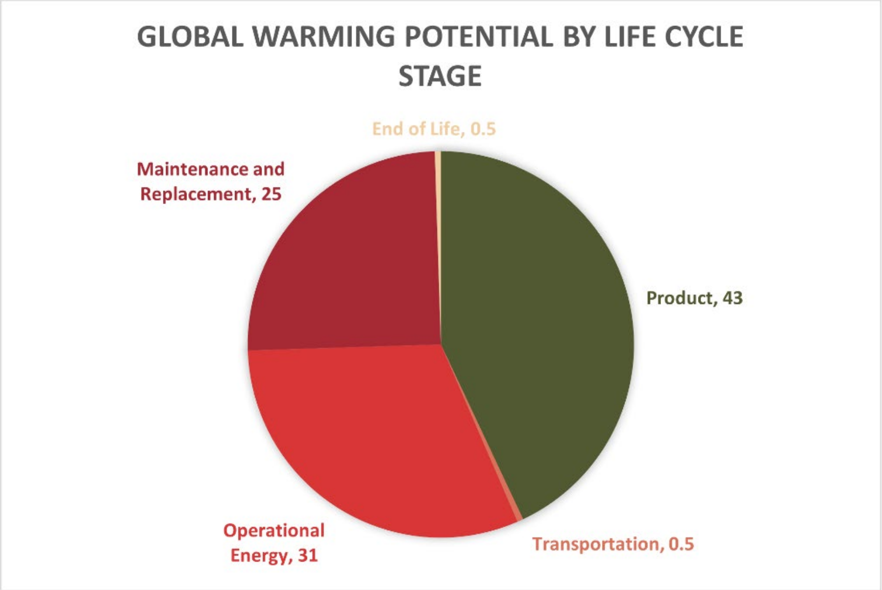


Figure 13: Global Warming Potential by Life Cycle Stage, intensive green roof

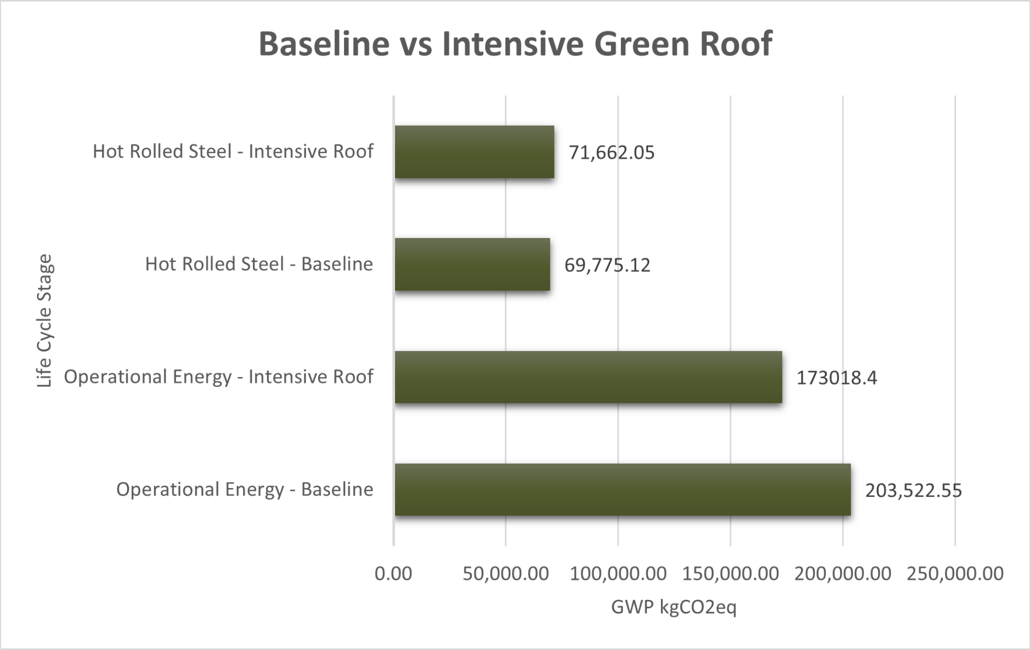


Figure 14:Global Warming Potential of Hot Rolled Steel and Operational Energy Comparison, intensive green roof vs. baseline

The findings – intensive green roof with deep soil

For the final green roof Life Cycle Assessment, an intensive green roof with a deep soil depth was analyzed. This roof is assumed to be able to support small trees or shrubbery in a rooftop environment. The values used for RISA-3D and Tally are listed below:

- Soil Depth is 12 inches
- Dead Load = 34 psf (original dead load) + 90 psf (saturated green roof material) = 124 psf
- Annual Energy Savings Percentage: 25%
    - Electricity = 4834 kWh
    - Natural Gas = 111 kWh

Due to the large decrease in operational energy savings and a decent increase in structural steel roof members, there is a noticeable difference in the global warming potential from the baseline. The building's Product contributed forty-five percent to the total GWP; the baseline model's Product contribution was forty-one percent. The operational energy's GWP for the model with an intensive roof is twenty-eight percent, which is a seven percent reduction when compared to the baseline model.

When breaking down the values for the GWP, the operational electricity is only contributing 150,820.80 kgCO$_2$eq to the total GWP for building of 366,222.86 kgCO$_2$eq. The hot-rolled steel GWP is up 2.9% when compared to the baseline model's hot-rolled steel GWP. Like the other intensive roof LCA, the values show that the operational energy is creating a larger savings than the increase in carbon emissions that hot rolled steel is creating.

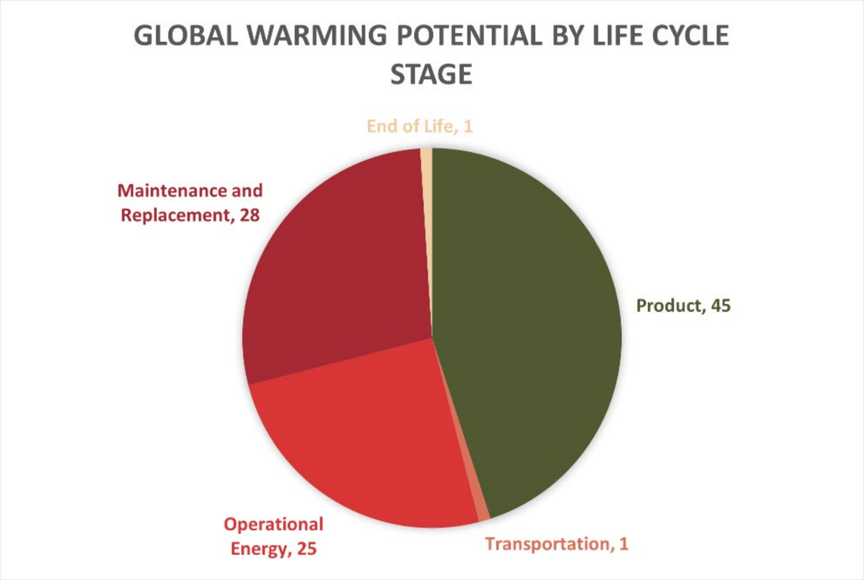


Figure 15: Global Warming Potential by Life Cycle Stage, intensive green roof with deep soil

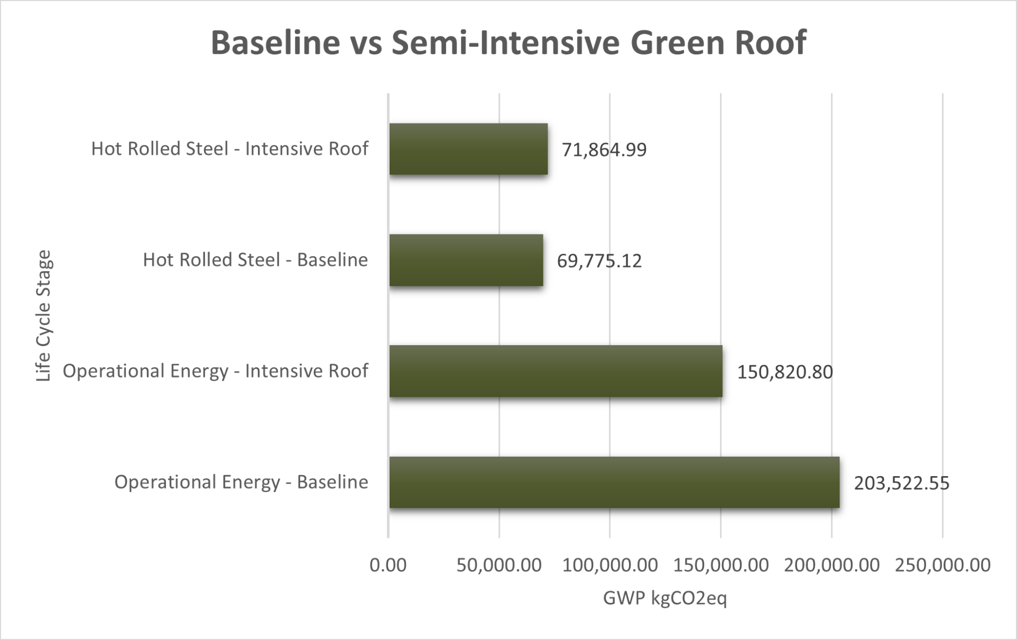


Figure 16: Global Warming Potential of Hot Rolled Steel and Operational Energy Comparison, intensive green roof with deep soil vs. baseline

Conclusion

After reviewing the Life Cycle Assessments from each model, there is an obvious immediate effect on the carbon footprint from both the increase in structural steel and the reduction in the annual operational energy. The increase in global warming potential from the larger steel members needed to support the weight from the vegetation and soil is relatively small when compared to the energy savings that green roofs can possibly produce. The research findings conclude that an intensive roof will significantly impact the operational energy, especially electricity usage. If a twenty-five percent savings on energy is possible from the building's climate and type of green roof designed, then this will immensely help reduce the building's overall GWP.

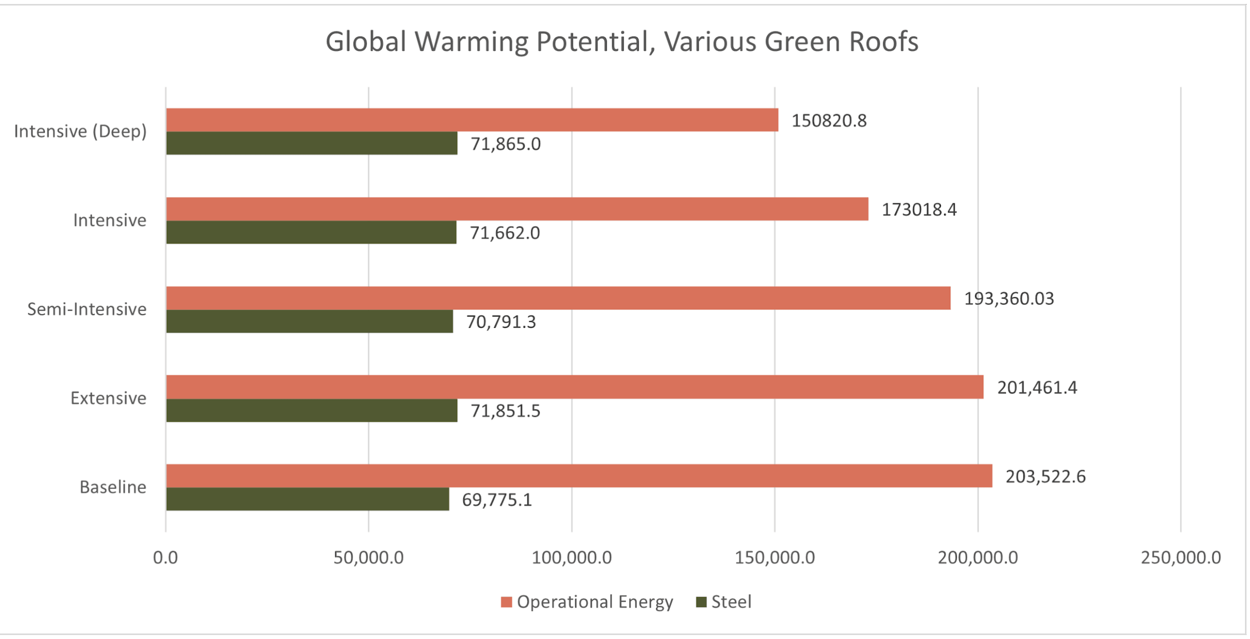
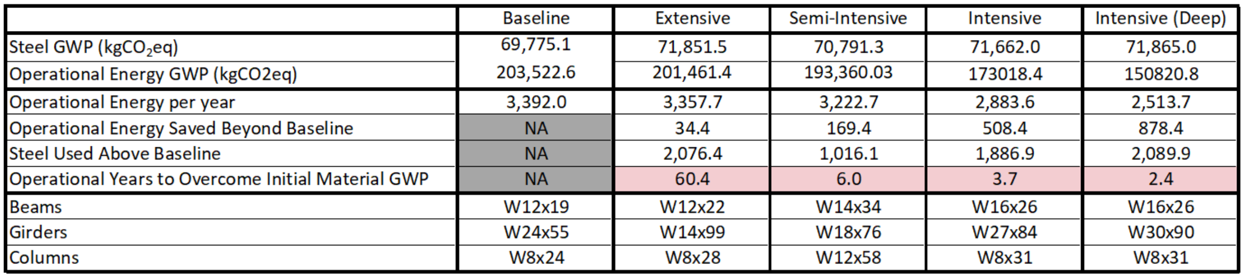


Figure 17: Comparison of Global Warming Potential of Steel and Operational Energy, all roof types vs baseline



	Baseline	Extensive	Semi-Intensive	Intensive	Intensive (Deep)
Steel GWP (kgCO$_2$eq)	69,775.1	71,851.5	70,791.3	71,662.0	71,865.0
Operational Energy GWP (kgCO2eq)	203,522.6	201,461.4	193,360.03	173018.4	150820.8
Operational Energy per year	3,392.0	3,357.7	3,222.7	2,883.6	2,513.7
Operational Energy Saved Beyond Baseline	NA	34.4	169.4	508.4	878.4
Steel Used Above Baseline	NA	2,076.4	1,016.1	1,886.9	2,089.9
Operational Years to Overcome Initial Material GWP	NA	60.4	6.0	3.7	2.4
Beams	W12x19	W12x22	W14x34	W16x26	W16x26
Girders	W24x55	W14x99	W18x76	W27x84	W30x90
Columns	W8x24	W8x28	W12x58	W8x31	W8x31

Figure 18: Summary of Findings for all roof types. Considering a 60-year cradle-to-grave life span

However, there needs to be a clear understanding of how much the green roof can typically save in that climate. The numbers used in this case study were generalized to allow for a comparison between the energy savings and embodied carbon from the initial increase in steel. The savings are going to vary due to the climate of the building's site, the vegetation placed atop the roof, and the depth of the soil. Due to many factors affecting the operational energy use of the building, the designer needs to do an in-depth analysis of whether a green roof makes sense with these variables. This is an important distinction to make when discussing the upfront cost and extra materials associated with a green roof, especially if a client's main desire is to save on energy.

Another factor that needs to be discussed when comparing these values is the fact that this case study was performed with a building that utilized steel as the structural material. If another structural material was used, like cast-in-place concrete or mass timber, the results would vary based on that material's GWP. Steel is a relatively sustainable material to use, due to its ability to be recycled; however, case studies with other structural materials need to be performed to truly understand how the structural demand on the building will affect the initial embodied carbon.

Overall, determining whether a green roof is a positive, sustainable choice is more complex than listing the accepted benefits of vegetative roofs and hoping for the same results with a different building. There is an initial increase in carbon emissions and there will be a continued carbon demand due to the increased maintenance of the roof. However, the other benefits like stormwater mitigation, reduction in urban heat island effects, increased biodiversity within cities, and savings on operational energy need to be analyzed for the building's current site location to see if the same results are possible.

Definitions

Embodied Carbon – the greenhouse gas emissions created from the transportation and production of materials and construction of the building

Extensive Green Roof – self-sustaining and natural vegetation placed in a rooftop environment, generally thin soil depths (Green Roof Technology)

Global Warming Potential – "measure of how much energy the emissions of 1 ton of gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide."[13] In units of $kgCO_2eq$.

Intensive Green Roof – high maintenance plants, including but not limited to perennials, grasses, bulbs, shrubs, and large trees, usually consists of 8 -30 inches of soil (Green Roof Technology)

Life Cycle Assessment – "in-depth analysis tool that conducts environmental impact assessments on whole buildings, manufactured building products, and material assemblies"

Operational Energy – energy needed to support the building's service during the life of the building, including energy for heating, cooling, lighting, and other building appliances

R -value – the measure of a material's (specifically insulation) ability to resist heat traveling through it

Semi-Intensive Roof – transitional roof type between extensive and intensive green roofs, usually native plants with a moderate need for maintenance (Green Roof Technology)

U-value – the inverse of a material's R-value, rate of heat transfer through the material by the difference in temperature

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