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Integrating Environmental and Cost Assessments for Data Driven Decision-Making: A Roof Retrofit Case Study

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Abstract. Existing buildings represent a significant portion of the real estate portfolio in the United States contributing to increased retrofits, renovations, and associated environmental impacts. A roof retrofit case study is presented to understand the leading factors in the building owner's decision in the context of results from environmental impacts to life cycle costs to retrofit design considerations. Two analyses, a life cycle assessment (LCA) and life cycle cost assessment (LCCA), were conducted on two different roof systems, a black EPDM (ethylene propylene diene monomer) membrane and a white PVC (polyvinyl chloride) membrane, for a maritime building located in the Philadelphia Navy Yard. The LCA and LCCA results showed that the black EPDM roof system was more viable compared to the white PVC roof system. The two roof systems had a similar impact on the building energy consumption with only a 1% difference. The LCA results found that production of the black EPDM system had 50% less global warming potential, 95% less eutrophication, and 60% less smog than the production of the white PVC system. Although the initial cost of the white PVC system was 7% more than the black EPDM system, the roof maintenance plan during the building use phase had a larger impact on the life cycle cost. These results were presented to the building owner, who indicated that cost was the deciding factor towards the future selection of a black EPDM roof system, despite initial interest in the myriad of results and analyses.

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Introduction. In 2013, the US building industry accounted for approximately 40% of the total US energy consumption (DOE 2014). The shift towards energy-efficient buildings built with environmentally preferred products has increased over the last 20 years, primarily in new construction. However, existing buildings represent a significant portion of the real estate portfolio in the United States; in the Northeast region alone 85% of commercial buildings, nearly 750,000, were built prior to 1990 (EIA 2003). The majority of products and materials within the building have a shorter life span than the building itself, contributing to increased retrofit and renovation applications. For many building owners, initial cost remains the key factor influencing their design decisions or product selections. To further understand retrofit impacts and decisions, a case study will be presented on the life cycle assessment (LCA) and life cycle cost assessment (LCCA) of two different roof options for a particular demonstration site.

Study Overview. The design of the LCA/LCCA integration study came to fruition under the Energy Efficient Building's (EEB) Hub, a DOE Innovation Hub, located in the Philadelphia Navy Yard. The demonstration site, Building 669, is also located in the Philadelphia Navy Yard and close proximity to the EEB Head Quarters, shown in Figure 1. Built in 1942, Building 669 is currently occupied by Rhoades Industries, a maritime company that has an 11-year lease on the building. Building 669 has two floors; the first floor is used as a mechanical workspace and connects to the dry dock while the second floor is used as the maritime offices for the company. There was an original whole building analysis study that occurred from 2012 to 2013 and included HVAC, envelope, lighting, glazing, and roof retrofits. During this original building analysis, it was evident from on-site visits that the roof system needed immediate attention; examples of deterioration are found in Figure 2. After the completion of the whole-building analysis, it was decided that a detailed study on roof systems would benefit the owner of Building 669, thus establishing the LCA/LCCA integration study. The goal of this study was to understand the leading factors in the building owner's decision in the context of results from environmental impacts to life cycle costs to retrofit design considerations.

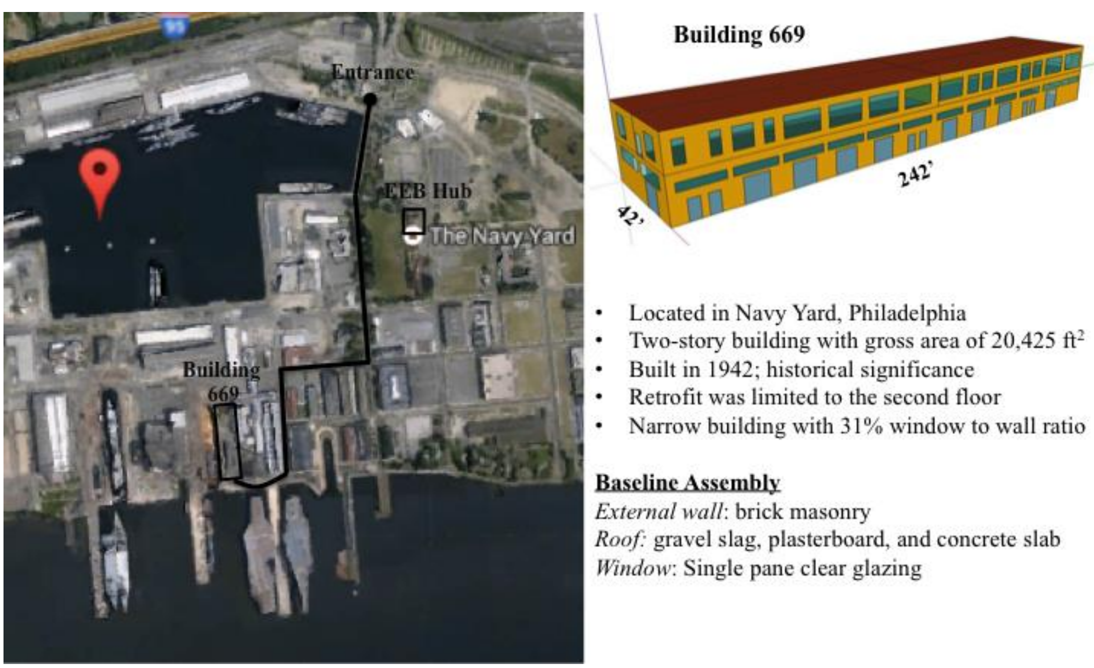

Figure 1. Building 669 Located in the Philadelphia Navy Yard

Figure 2. Pictures from Inside Building 669 (August 2012)

The Building 669 owner requested a roof capable of supporting PV (photovoltaic panels) and a cool roof option; the options selected for the LCA/LCCA study included a black EPDM (ethylene propylene diene monomer) membrane system and a white, PVC (polyvinyl chloride) membrane system, shown in Figure 3. Approximately 25% of roofs in the Northeast region are composed of plastic, rubber, or synthetic sheeting and while EPDM is the most popular single-ply roof membrane in the US, PVC is a growing roof membrane option (EIA 2003, Smith 2014). Both membrane options used a roof section consisting of 4.72” concrete, a vapor barrier, R-30 polyisocyanurate rigid board insulation, and 0.5” Dens Deck roof board with the membrane applied on top. The EPDM membrane required a Kraft paper backing between the Dens Deck and the membrane.

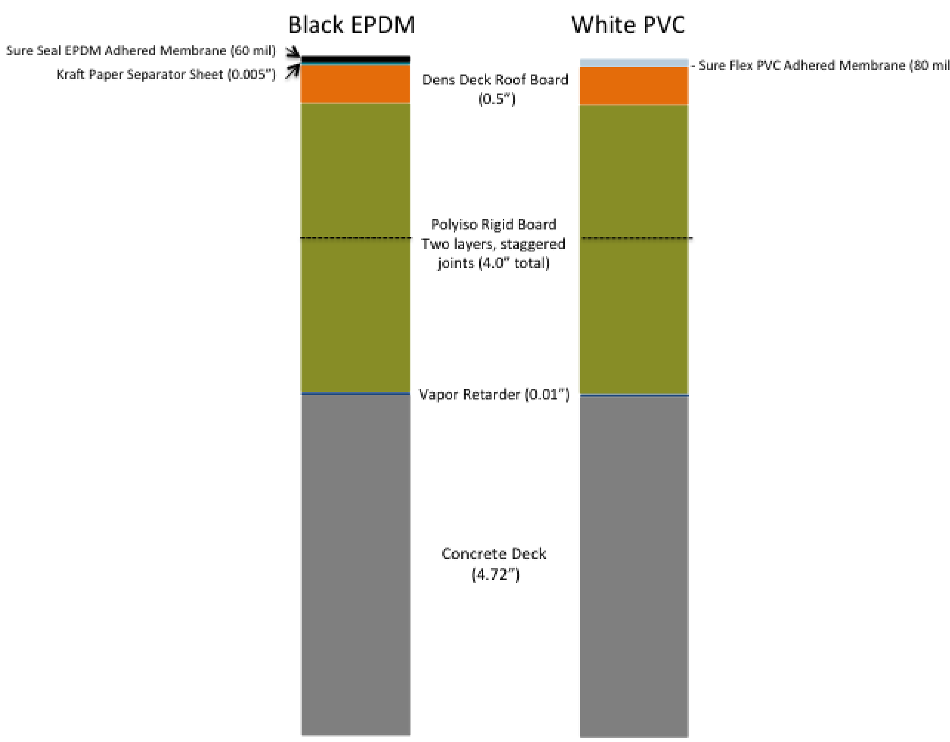

Figure 3. Cross-Section of Roof Material Alternatives

Methods. For this case study, industry information was gathered on the two different roof options. First, a comparative LCA on the materials used in both roof options and the building energy consumption over the roof's estimated lifespan, 20-years, was determined. Second, an LCCA of the roof materials, energy use, and roof end-of-life was quantified. Last, the data for the two assessment methods were integrated together and presented to the building owner as part of the decision making process.

Life Cycle Assessment. LCA is a universal tool used to analyze the environmental impacts of a product or process from raw material extraction to production, use, and end-of-life (EOL) (ISO 1997, Baumann and Tillman 2004). LCAs are standardized by the ISO 14040 series and there are four main steps to an LCA: 1) goal and scope; 2) life cycle inventory; 3) life cycle impact assessment; 4) interpretation (ISO 1997).

This LCA was a direct comparison between the two different roof systems suggested for Building 669. The system boundary is cradle to gate; therefore the assessment takes a look at the raw material extraction, product manufacturing, installation of the roof layers, and building energy use; an overview of the study system boundary is shown in Figure 4. End-of-life is not included in the analysis. The functional unit for this assessment is the entire area of Building 669's roof, which is 10,212 ft^2.

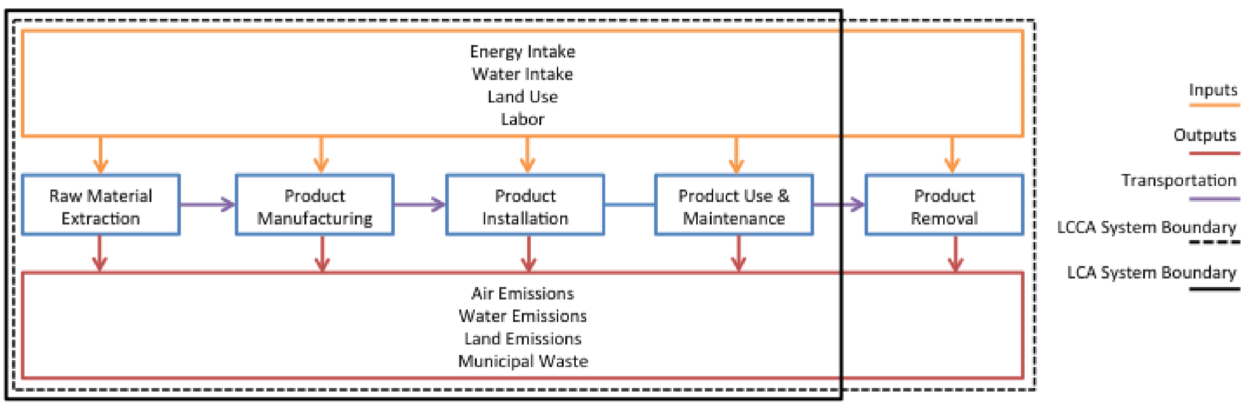

Figure 4. System Boundary of LCA/LCCA Roof Systems

For the life cycle inventory of this comparative LCA, the Athena program was used. Athena creates a platform to calculate the environmental impacts specific to building systems, where a majority of their database inventory comes from industry-specific data (Bowick, O'Connor et al. 2014). Utilizing Athena made it possible to get US material information that was likely more accurate than other LCA programs and/or databases; for example, the polyiso rigid board material found in Athena was from an internal Bayer MaterialScience study, the company product used for both the EPDM and PVC roof systems (ASMI 2012). Because there are set values assigned to most of the data points in Athena, a weighting factor was applied to accurately represent the roof material layers in each system according to the roof design, Table 1. For example, the PVC membrane in the roof design is 80 mil while the largest PVC roof membrane in Athena is 48 mil, therefore the LCA results for the PVC membrane were multiplied by a factor of 1.67 to represent the study roof design. Athena uses TRACI v2.1 as the impact assessment method.

Table 1. Life Cycle Inventory for the Roof Materials via Athena

Roof Description	Athena Unit Process	Factor
EPDM Membrane (60 mil)	EPDM Black 60 mil	1
PVC Membrane (80 mil)	PVC 48 mil	1.67
Kraft Paper (0.005")	PP Scrim Kraft Vapor Retarder Cloth	1
Dens Deck (0.5")	Moisture Resistant Gypsum Board (0.5")	1
Polyiso Rigid Board (4")	Polyiso Foam Board (unfaced) 1"	4
Vapor Retarder (0.01")	3 mil PE (0.03")	0.34

The environmental impacts for the building's energy consumption were also included in the study. eQuest v3.64, a free program designed by the DOE, was used to analyze the energy consumption of the study building. Separate files were created within eQuest to specify the reflection, absorptance, and emittance for the black EPDM and white PVC membranes. The energy consumption was divided into cooling and heating loads; the cooling load adjusted for electric window units with a 3.4 coefficient of performance and the heating load is natural gas. Building 669 was modeled as is, with no changes; the roof was then replaced with the two options proposed and the energy model recalculated. Considering the 20-year life span of the roof materials, the energy consumption for the building also accounted for 20 years.

Life Cycle Cost Assessment. Life cycle cost assessment (LCCA) is a tool to understand the costs incurred throughout the life of a building or a building system (Asiedu and Gu 1998, Durairaj, Ong et al. 2002b, Dunk 2004, Fuller 2010). This includes the cost to produce and transport materials, construct, maintain, and end-of-life (EOL). A simple LCCA calculates the direct costs in net-present value (NPV), represented in Equation 1 (Durairaj, Ong et al. 2002a, Dunk 2004, Russell 2009).

$$\mathbf{NPVTC}(\boldsymbol{t}) = \sum_{\boldsymbol{i}=\mathbf{1}}^{\boldsymbol{t}} \frac{[\boldsymbol{UC}(\boldsymbol{i}) + \boldsymbol{M}\&\boldsymbol{R}(\boldsymbol{i})]}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{t}-\mathbf{1}}} + \frac{\boldsymbol{Replacement\ Cost}}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{t}-\mathbf{1}}} + \sum_{\boldsymbol{i}=\boldsymbol{t}+\mathbf{1}}^{\boldsymbol{t}} \frac{[\boldsymbol{UC}(\boldsymbol{i}-\boldsymbol{t}) + \boldsymbol{M}\&\boldsymbol{R}(\boldsymbol{i}-\boldsymbol{t})]}{(\mathbf{1}+\boldsymbol{r})^{\boldsymbol{t}}}$$

Equation 1. Net Present Value of Total Cost for a Life Cycle Cost Assessment. t = replacement year, r = discount rate, i = evaluation year, UC = user cost, M&R = maintenance and repair cost, replacement cost = estimated replacement cost (Coffelt and Hendrickson 2010)

The LCCA encompassed the entire life cycle of the roof from material production to installation to maintenance and product material. Data collection for the LCCA included the sources of Carlisle SynTec, the Center for Environmental Innovation in Roofing, and CP Rankin; shown in Table 2. For the cost assumptions, an industry standard of 20-year lifespan (2013-2033) was assigned to the study (Cash 2006, Hoff 2007, Coffelt and Hendrickson 2010, DPR 2013). An inflation rate of 3% was included in the net-present value of all the calculations (McHahon 2014). An installation cost estimate was determined in February 2013 by a local Philadelphia estimating company for the two roof options and included the removal of the current roof system down to the concrete deck, any necessary plumbing, materials and labor of the new roof, and a 20-year built-in warranty that guarantees material replacement and repairs if necessary. The future replacement and removal costs were projected from the February 2013 roof estimate.

Table 2. Life Cycle Cost Assessment Data Collection

Roof Description	Data Collection
EPDM System Installation	CP Rankin
PVC System Installation	CP Rankin
Maintenance Plan	CEIR and Carlisle Syntec
Removal Cost	CP Rankin
Building Energy Cost	eQuest data & CBEC data

One area for concern in regards to a roof's life cycle cost is the decision to have a maintenance plan (Hoff 2007, Coffelt and Hendrickson 2010, Vross 2012, DPR 2013). This analysis examined two different maintenance plans, a reactive plan and a proactive plan. A reactive maintenance plan only responds to major roof situations, such as a leak or a material malfunction. A proactive maintenance plan is a more active approach, including quarterly inspections by professionals who check the roof seams, clear any drains, and test for moisture infiltrations among other things. A 15-year industry study found that the average building owner with a reactive maintenance plan pays approximately \$0.25/ft^2/year over a roofs life span with an average roof replacement at year 13 while a building owner with a proactive maintenance plans pays approximately \$0.14/ft^2/year with an average replacement at year 21 (Vross 2012, DPR 2013). Having a proactive maintenance plan has a considerable impact on the life cycle cost of a roof system.

Limitations. For the LCA, the environmental impacts associated with the roof maintenance plans and the roofs end-of-life were not considered. For the LCCA, potential carbon tax credits and other green material benefits were not included. Creating more linkages between the LCA and the LCCA, such as the cost and environmental benefits of the maintenance plan, could improve the tools building owners use for their decision-making.

Results.

Life Cycle Assessment. An overview of the LCA results can be found in Figure 5. The results show that the PVC membrane has significantly higher environmental impacts compared to the EPDM membrane. The manufacturing of PVC includes chlorine, cancer causing vinyl chloride monomer, and toxic additives (SPI 2009, APME 2013, North and Halden 2013, Rochman, Browne et al. 2013). Additionally, PVC generates large quantities of waste. However, in one category, fossil fuel consumptions, EPDM and PVC are similar, which implies that both of these materials require large amounts of energy to produce and manufacture.

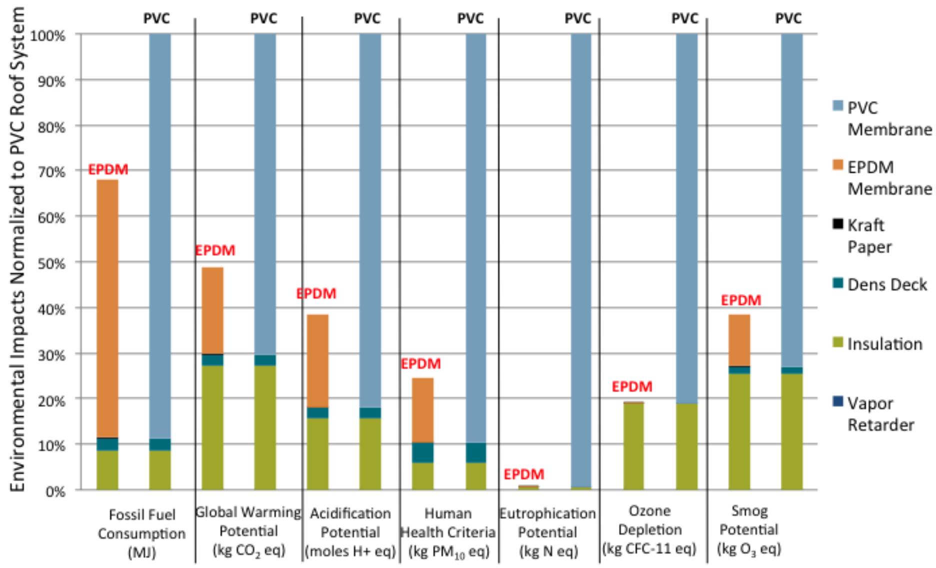

Figure 5. LCA results of roof scenario materials. PVC = polyvinyl chloride; EPDM = ethylene propylene diene monomer

Taking into consideration the use phase of Building 669, an LCA of the energy consumption was also analyzed. The LCA results show that the energy consumption, especially the cooling loads, dominated all environmental impact categories **Figure 6**. Utilizing a PVC membrane resulted in a lower cooling load by approximately 1% over the EPDM membrane, while heating loads were about equal.

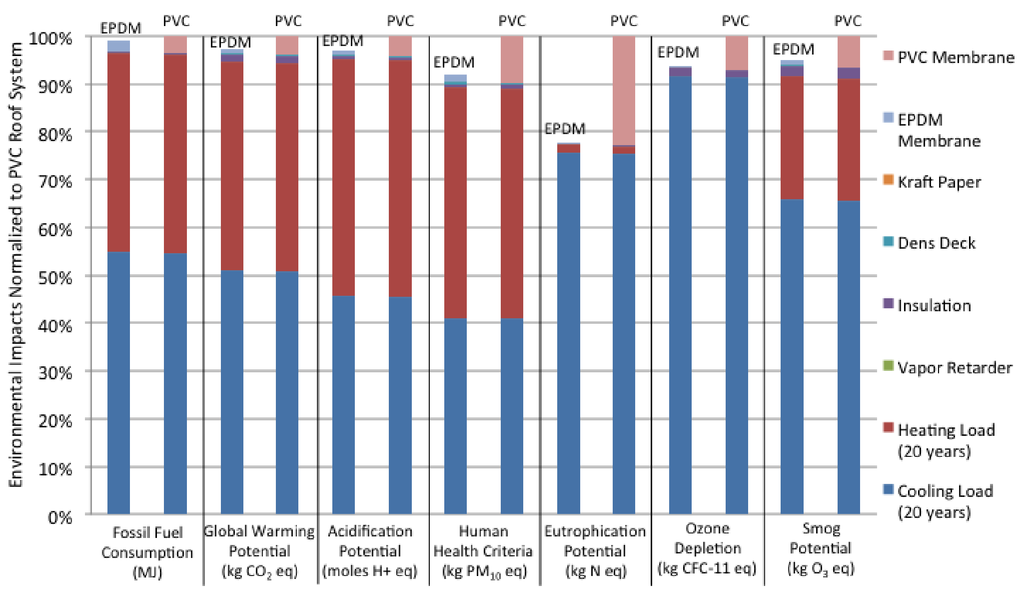

Figure 6. LCA of roof options including material production and building use energy consumption. PVC = polyvinyl chloride; EPDM = ethylene propylene diene monomer

Life Cycle Cost Assessment. An overview of the LCCA results can be found in Figure 7. The life cycle costs articulate the importance of a roof maintenance plan and its effect on what year a replacement roof is needed (either year 13 or year 21) (Vross 2012, DPR 2013). The study utilized the energy model, as previously described, to understand Building 669's potential in energy saving costs due to a new roof. For both the black EPDM and the white PVC membrane options, there was approximately 12% energy saved in the cooling season and approximately 28% energy saved in heating season. In the LCCA, an average of 20% reduction in energy consumption as applied for the use phase.

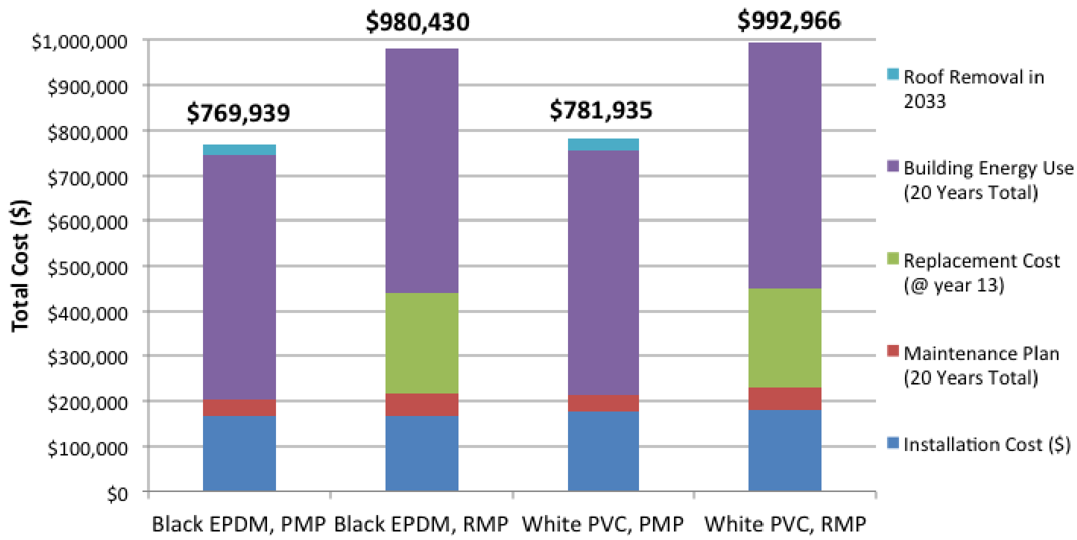

Figure 7. Life Cycle Cost Assessment of Roof Options for Building 669; RMP = Reactive Maintenance Plan; PMP = Proactive Maintenance Plan; PVC = polyvinyl chloride; EPDM = ethylene propylene diene monomer

Recommendation. Based on the LCCA and LCA results of the two different options, it is recommended that Building 669 use a black EPDM roof with a proactive maintenance plan for their retrofit option. For this specific case study, both the LCCA and LCA results had the black EPDM roof system as the more viable option compared to the white PVC roof system. It was important to present and interview the Building 669 owner on the LCCA/LCA process to gather feedback on realistic applications for future retrofit projects (Stutman and Gorgone 2014).

The LCCA analysis proved to be more of interest to the Building 669 owner as well as other members of the EEB Hub and PIDC (Philadelphia Industrial Development Corporation), the building management company for most of the Philadelphia Navy Yard. Specifically, installation cost, operating costs, periodic replacements & repairs, and end-of-life disposal/salvage value were more important than knowing or understanding the material and production costs found in the beginning of a product life cycle. One key takeaway from the interview with the Building 669 owner, the director of sustainability for PIDC, and the Demonstration Project Manager for the EEB Hub was that a typical bank loan for a small- to medium-sized company is about $20/sf for retrofits and renovations (Stutman and Gorgone 2014). The building owner is going to look at initial costs first, maintainability second, and then other life cycle costs and/or energy considerations.

The LCA results were challenging to valuate for the Building 669 roof retrofit. The PVC membrane was the largest contributor in environmental impact categories, followed by the EPDM membrane and the polyiso-rigid board insulation. Due to the nature of Rhoades Industries, the most important environmental impact to the building owner is air permitting, specifically the Pennsylvania Title V permit. Any analyses that provide an opportunity for credit reductions would be more appropriate than a full LCA. However, it was made apparent that a larger corporation, which may invest in more than one property, may benefit from LCA, especially in relation to green building rating systems, such as LEED.

The feedback gathered from the Building 669 owner and members of the EEB Hub and PIDC have helped develop lessons and strategies for future LCCA/LCA application: (1) Budget requirements are extremely important; (2) Client goals and/or programs should be known (i.e., LEED certification, environmental permitting requirements, company mission); (3) Companies (typically larger) with more available capital are more likely to invest in LCCA and/or LCA analyses. In conclusion, the LCCA and LCA results were appreciated by the building owner, but not entirely realistic for a small- to medium-size company looking to do a roof retrofit.

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