CONSTRUCTION OF EFFICIENT, COST-EFFECTIVE AND SUSTAINABLE MAINTENANCE FACILITIES

Final Report

PROJECT 792

RESEARCH

Oregon Department of Transportation

CONSTRUCTION OF EFFICIENT, COST-EFFECTIVE AND SUSTAINABLE MAINTENANCE FACILITIES

Final Report

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Abstract: The Oregon Department of Transportation (ODOT) manages about 89 maintenance stations. Many of these are reaching or beyond their life expectancy, inefficient, or functionally obsolete (e.g., unable to accommodate large modern equipment). There is an urgent need to systematically replace these buildings to support the maintenance mission of the agency. By reviewing literature, green building standards and rating systems, and other DOT regulations, and by conducting two case studies as part of an ODOT research project (SPR 792), best practices were identified to be considered when constructing new or renovating existing stations. First, optimizing building energy performance appears to be the single most important action that can result in cost savings and reduce its negative environmental impacts. To optimize energy use, it is important to perform initial ***commissioning of building systems*** ensuring that the HVAC and electrical systems (including sensors) are operating per manufacturer recommended specifications. Then, using ***building energy simulation tools*** is recommended to optimize energy performance and to identify areas where energy can be saved, or where waste energy can be harvested. Next, it was found ***making improvements in sustainability metrics for materials used in the greatest quantity*** on a mass (or volume) basis can result in significant improvements in overall sustainability performance. Also, ***prioritizing the use of regional materials*** for the most used building materials, especially those of greatest density (e.g., concrete), can significantly reduce environmental impacts of associated transportation, as well as stimulating the local/regional economy. Finally, focusing on ***materials that provide synergistic benefits in energy savings*** was found to be important for improving the overall sustainability performance of buildings.

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Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH					LENGTH				
in	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
AREA					AREA				
in2	square inches	645.2	millimeters squared	mm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.093	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd2	square yards	0.836	meters squared	m^2	m^2	meters squared	1.196	square yards	yd2
ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi2	square miles	2.59	kilometers squared	km^2	km^2	kilometers squared	0.386	square miles	mi^2
VOLUME					VOLUME				
fl oz	fluid ounces	29.57	milliliters	ml	ml	milliliters	0.034	fluid ounces	fl oz
gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
*NOTE: Volumes greater than 1000 L shall be shown in m^3.									
MASS					MASS				
oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000 lb)	0.907	megagrams	Mg	Mg	megagrams	1.102	short tons (2000 lb)	T
TEMPERATURE (exact)					TEMPERATURE (exact)				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C	°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

There are approximately 89 maintenance stations managed by the Oregon Department of Transportation (ODOT), and a large assortment of other sheds, storage, and support buildings. Many of these maintenance stations are reaching the end of their usable life, beyond their life expectancy, inefficient, or functionally obsolete (e.g., unable to accommodate larger-size, modern equipment). There is an urgent need to systematically replace these buildings to support the agency maintenance mission. A typical maintenance station can cost from $8 to $20 million, representing a significant capital cost burden over the next several years. The Oregon DOT Facilities Leadership Team (representatives from all Highway Division Regions) has updated a 10-year plan prioritizing the renovation and replacement of maintenance stations (January 2014). The land purchase, design, and site preparation phase for one facility, and the construction phase of a second facility will be accomplished each biennium at funding of approximately $12 million. Another important consideration in these efforts are requirements for any new buildings constructed by authorized state agencies to exceed current building energy codes by 20% and for any public building costing over $1 million to devote at least 1.5% to green energy technology. ODOT facilities are also required to adhere to the latest State Energy Efficient Design (SEED) rules. It is the intent of ODOT to exceed these latest regulations. A new maintenance station recently constructed in Sisters became the first in Oregon to incorporate renewable energy – in the form of geothermal heating and solar water heating. Even more sustainable and cost-effective solutions could have been accomplished by utilizing high performance design practices, sustainably produced materials, increased insulation, more efficient lighting, water-saving techniques, waste reductions, and other measures. There is a need to develop guidance to realize such sustainable and cost-effective solutions in new construction for ODOT.

One of the main goals of this project is to develop a best practice guide that will enable ODOT to specify, design and construct sustainable, energy efficient and cost-effective maintenance stations in the years to come. To realize this goal the sustainability of two current ODOT maintenance stations (in Sisters, Oregon and Albany, Oregon) were evaluated to serve as case studies to help inform the research team and ODOT about the most effective and promising sustainability measures. Based on the scope of this project, a modified life cycle assessment (LCA) and a modified life cycle cost analysis (LCCA) were conducted on the two maintenance facilities. The modified LCA and LCCA focused on energy and materials use and impacts. The modified LCA provided quantitative data to illustrate the current base-case energy demands and how they have been met. This information was then used to identify the life cycle phases and processes that consume the most energy and, therefore, require improvement for environmental impact reduction. The focus on materials provided information about the environmental impacts of selected materials and alternatives to aid in choosing environmental-friendly materials that are also cost efficient.

This document provides the detail on the background knowledge and methodology used performing the modified LCA and LCCA, as well as the study findings for the two alternative facility design cases. The results of the two studies are then used to inform the creation of the Best Practices Guide.

1.1 OVERVIEW OF THE ALBANY MAINTENANCE FACILITY

The Albany maintenance facility was built in 1995 and has three buildings on site including a main building, a maintenance bay building, and a fuel station. The main office and the maintenance facility are within the main building, which is a 14,500 ft^2 pre-manufactured metal structure. Standing seam metal panels were used as the roof, and metal panels were also used as the external wall siding material. Insulation was applied to the interior surfaces of both the roof and the external walls of the building. A concrete apron was cast at each truck bay area. The maintenance bay building is a 9,600 ft^2 wood pole structure, largely open on both sides. Metal roofing and metal siding were also used in this building. The interior bearing partition consists of 3-1/2" wood studs and gypsum boards on each side.

Electricity is the main power supply for the maintenance station. In addition, diesel is stored for backup fuel for maintenance vehicles. LED lights are used in the maintenance area of the main building. The station is occupied 24 hours a day in winter time and is somewhat less occupied during the summer (occasionally 24 hours a day). For waste water catchment, an oil filter and a rock filter system are used to control releases of contaminated runoff. The property also houses six large tanks for storing road deicer (magnesium chloride).

1.2 OVERVIEW OF THE SISTERS MAINTENANCE FACILITY

The Sisters maintenance facility was built in 2012. This facility includes two buildings on site: a maintenance building and an equipment building. The maintenance building is a 10,260 ft^2 single-story metal structural building, which includes vehicle-maintenance bays and personnel support areas. The exterior walls consist of medium density overlay (MDO) plywood sheathing, glass fiber board insulation, and gypsum board. The interior partition wall consists of stud wood and gypsum boards on each side. The roof is made of metal. Solar panels and skylights are installed on the roof. The equipment building is a 5,400 ft^2 single-story wood pole, open front building. This building is mainly used for equipment and de-icing salts storage (in a fluid tank). The siding materials and the roof used for the equipment building match the materials used in the maintenance building.

In 2004, Department of Administrative Services (DAS) issued the Sustainable Facilities Standards and Guidelines (Oregon State University, n.d.). Accordingly, all new state construction and major renovation must meet Leadership in Energy and Environmental Design (LEED) Silver equivalency. In order to meet these requirements, different actions were taken during the design and construction of the Sisters maintenance facility. For example, the facility was built with low-emitting volatile organic carbon (VOC) materials to improve indoor air quality. Also, a hybrid heating system, which consists of a solar-thermal heat system (using a flat-plate solar collector) and a geo-thermal heat system (using a closed horizontal ground loop), was installed in the maintenance facility.

The following sections present the methodology used for the LCA and LCCA studies, as well as how this information will be used to inform the Best Practices Guide.

2.0 LITERATURE REVIEW

Conducting modified LCA and LCCA studies can inform decision-makers about more efficient, life-long cost-effective, and more sustainable alternatives for construction of maintenance facilities. This review of the literature covers topics including LCA, LCCA, commonly used standards and rating systems, and current DOT regulations and case studies from across the U.S. In Section 2, the stages of an LCA study and the available LCA methods and databases are reviewed. Next, LCCA principles and methods are presented in Section 3. The three most commonly used rating systems for sustainable construction in the U.S. are introduced and reviewed in Section 4. In Section 5, ODOT SEED rules, regulations from other state DOTs, and exemplary case studies that helped to inform the research team in the development of the best practices guide are reviewed.

2.1 LIFE CYCLE ASSESSMENT (LCA)

2.1.1 LCA Overview

LCA is a "cradle-to-grave" technique to assess the environmental aspects and potential impacts associated with a product, process, or service (United States Environmental Protection Agency, 2006b). It encompasses all processes and environmental outputs beginning from extraction of raw materials to the final disposal stage. The U.S. Environmental Protection Agency (United States Environmental Protection Agency, 2006b) provides thorough instructions on how to perform an LCA.

The benefits of LCA have been recognized by increasing numbers of organizations, from private industries to the public sector. By evaluating LCA results, decision makers can identify critical stage(s) within the life cycle of the product or process to effectively select a better alternative and propose changes to the business strategies, construction practices, and maintenance procedures. In addition, transparency has become a goal for organizations to gain community's trust and support. Perhaps the biggest advantage of LCA is the ability to account for the replacement of environmentally impactful inputs, such as replacing an inefficient piece of equipment or purchasing reusable materials in place of raw materials.

2.1.1.1 *Phases of an LCA*

An LCA typically consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation. In addition to providing the principles and guidelines for LCA (United States Environmental Protection Agency, 2006b), the EPA also provides general guidelines on performing Life Cycle Inventory Analysis (LCIA) (B. W. Vigon & United States Environmental Protection Agency, 1993), LCIA quality assessment (United States Environmental Protection Agency, 1995a), and LCIA methods (United States Environmental Protection Agency, 1995b). The ISO 14000 family of standards, including ISO 14040 Life Cycle Assessment Principles and Framework (International Organization for Standardization,2000), ISO 14042 Impact

Assessment (International Organization for Standardization,1998), and ISO 14043 Life Cycle Interpretation (International Organization for Standardization, 2000), provide a standardized methodology for conducting the various phases of an LCA.

2.1.1.2 ***LCA for Buildings***

The construction or renovation of buildings may produce environmental and health impacts such as asbestos, nitrogen oxide, inorganic lead, silicon, and toxic organic compounds (e.g. benzene). Benzene, for example, can lead to acute and long-term health consequences to on-site construction workers and near-by residents (Barry S. Levy, Wegman, Baron, & Sokas, 2011, pp. 763–765). In addition, continuing use of existing conventional buildings and energy systems requires fossil-based energy consumption, which contributes to significant air pollution such as particulate matter, carbon monoxide, and toxic organic compounds (Barry S. Levy et al., 2011, p. 150). This has raised an urgent need for energy-efficient buildings. A study found that renovating buildings for improved energy efficiency can lead to smaller construction phase carbon loads, while achieving the same reduced use phase energy consumption goals as new energy efficient buildings (Säynäjoki, Heinonen, & Junnila, 2012). The same study found that the carbon payback period spans a few decades in the case of constructing new energy efficient buildings. Therefore, LCA studies for buildings are needed to evaluate all factors that contribute to the environmental consequences of each alternative, including spatial and temporal factors, e.g., location and building codes (United States Environmental Protection Agency, 2006b), which are unique for each case.

2.1.2 Phase 1: Goal and Scope of LCAs on Buildings

First, the goal (objective) and scope (system boundary) for an LCA must be defined. The goal is often clear, determined by an external motivator for the study (e.g., the need to reduce building energy use). The system boundary stems from the study goal, but also depends on the type of study undertaken, as discussed next.

2.1.2.1 ***Types of LCA Undertaken***

Attributional LCA attempts to answer “how are things flowing within the chosen temporal window?” e.g., comparing the potential impacts of constructing a green building versus renovating an old building.   Consequential LCA attempts to answer “how will flows change in response to decisions?” e.g., comparing the change in impacts due to a change in demand that follow a decision to replace a high impact process with a more environmental-friendly process. Furthermore, LCA can investigate situations or changes that occurred in the past (retrospective LCA) or will occur in the future (prospective LCA). Therefore, the LCA performed can take one of the four following perspectives: retrospective attributional, prospective attributional, retrospective consequential, and prospective consequential (Curran, Mann, & Norris, 2005). In addition, an important part of defining the scope of an LCA is the desired specificity of the study, which refers to whether the data collected must be specific to one organization or industry, or more generalizable for common industry practices.

2.1.2.2 *Functional Units Considered*

Determining the appropriate Functional Unit (FU) plays an important role in LCA. A FU describes the function of the product or process being studied, so that the basis of comparison between two products should be of equivalent use (United States Environmental Protection Agency, 2006b). The common FUs for LCA of both residential and commercial buildings are usually in the form of impact per area per year (e.g., $kWh/ft^2/yr.$ or $kg\ CO_2/m^2/yr.$) (Kneifel, 2010a; Zabalza Bribián, Aranda Usón, & Scarpellini, 2009a), which allows extrapolation for buildings of various sizes. Some studies compare the impacts per building when comparing buildings of similar sizes and uses (Ghattas, Gregory, Olivetti, Greene, & Hub, 2013a).

2.1.2.3 *Life Span Considered*

The life of the buildings also needs to be determined for fair comparison. Life of buildings typically ranges from 25 to over 100 years, with an average of 50 years (Ghattas et al., 2013a). Municipal buildings are most likely to go through multiple renovation periods; therefore a 100-years life time can be implied. However, a 50-year life time has been recommended for analysis of buildings, when pursuing a greenhouse gas (GHG) reduction goal (Säynäjoki et al., 2012). This is consistent with ODOT's intent for the Sisters Maintenance Station building to have a 50-year life (R&W Engineering, 2015a).

2.1.2.4 *Life Cycle Stages Considered*

A typical life cycle of a building includes three main stages: production, management, and destruction (Adalberth, 1997a). The production phase consists of manufacturing of the building materials, transportation, and erection. The management phase consists of occupation, maintenance, and renovation. The destruction phase consists of demolition and removal. Prior work (Zabalza Bribián et al., 2009a) considered the construction process as a separate phase, and included maintenance, repair, refurbishment, and operational water use in the occupation category, and recycling and reuse in the end-of-life (destruction) phase. Including recycling and reuse activities can better account for current industry practice. A more detailed breakdown of the life cycle phases will help identify the main sources that create significant (consequential) differences in impact results. For example, while the comparison of two building types might incur the same energy and material impacts for "normal" maintenance activities, e.g., painting and carpet replacement, operational water use and operational energy use, such as cooling and heating can be significantly different.

Table 2.1 presents the life cycle stages and sub-stages for a building as proposed by (Zabalza Bribián et al., 2009a). The table helps identifying the main sources of energy and material consumption to aid in system boundary definition and allocation of inputs for comparison of design alternatives. Thus, material and energy flows can be more accurately accounted and more easily managed.

Table 2.1. Life Cycle Stages and Sub-stages for a Building

Stage	Sub-stage
Production	Raw materials supply
	Transportation
	Manufacturing
Construction	On-site processes
	Transportation
Management	Maintenance
	Repair and replacement
	Renovation
	Operational energy use
	Operational water use
Deconstruction	Demolition
	Recycling and reuse
	Transportation
	Disposal

2.1.3 Phase 2: Life Cycle Inventory for Building Studies

A Life Cycle Inventory (LCI) is "a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a product, process, or activity" (United States Environmental Protection Agency, 2006b). This study focused on gathering energy use data and information about materials inflows and outflows. Completing an LCI consists of four steps:

- Develop a process flow diagram for the system being evaluated
- Develop a data collection plan
- Collect data (e.g., material and energy inputs and outputs)
- Evaluate and report results

A comprehensive list of all components for the building under study is needed to account for all material inputs (building components) and outputs (e.g., solid, liquid, and gaseous emissions). The MasterFormat standard developed by the Construction Specifications Institute (CSI) and the UNIFORMAT II standard by ASTM International have been found to provide sufficient organization of a typical building's structure to assist completion of a comprehensive LCI, as discussed below.

2.1.3.1 *MasterFormat Standard (Construction Specifications Institute (CSI))*

MasterFormat is the specifications-writing standard for most commercial building design and construction projects in North America. It provides a list of numbers and titles for the various building components classified by work results. Its primarily use is "to organize project manuals, detailed cost information, and other information in later stages of design and construction" (CSI, 2014a).

2.1.3.2 *UNIFORMAT II Standard*

ASTM International published the UNIFORMAT II standard to help organize input data for buildings (Charette & Marshall, 1999). While similar to the MasterFormat standard, UNIFORMAT II arranges construction information based on "systems" or "assemblies", which are "functional elements, or parts of a facility characterized by their functions, without regard to the materials and methods used to accomplish them" (CSI, 2016).

2.1.4 Phases 3-4: Life Cycle Inventory Assessment (LCIA) and Interpretation

2.1.4.1 *LCIA Methods Considered*

LCIA can to establish the linkage between the product or process and its environmental and human health impacts (United States Environmental Protection Agency, 2006b). Impact assessment addresses ecological effects, human health effects, and resource depletion. Mapping life cycle impacts from life cycle inventory data is a complex process grounded in environmental science. Some linkages are determined using broad assumptions, resulting in high levels of uncertainty, while other direct linkages from inventory information to environmental impacts have not been established (or only indirect linkages may exist). Key steps that comprise an LCIA are discussed below, using Eco-Indicator 99 as an example LCIA method.

2.1.4.2 *Selection and Definition*

First, the Selection and Definition of Impact Categories step focuses on selecting the relevant impact categories, guided by the goal and scope definition phase. The total impacts are grouped into 11 impact categories: global warming, stratospheric ozone depletion, acidification, eutrophication, photochemical smog, terrestrial toxicity, aquatic toxicity, human health, resource depletion, land use, and water use.

2.1.4.3 *Classification*

Second, under Classification, the LCI results can be organized into the selected impact categories. LCI data results such as kg-CO_2, kg-NO2, and toxic chemicals with reported lethal concentration for 50% population (LC50), can be assigned to one or more impact categories. If the effect endpoints are independent, i.e., ozone depletion and acidification, the LCI data that is being considered for the two effect endpoints can be allocated 100% into each endpoint. If the effect endpoints are dependent, partition of the LCI data is required in order to allocate the appropriate proportion into the endpoint to which they contribute.

2.1.4.4 *Characterization*

Third, in the Characterization step, science-based conversion factors, called characterization factors, are used to convert different LCI data into the equivalent impact of interest, e.g., global warming potential, within each impact category. The formula for impact characterization is:

$$\textbf{\textit{Impact Indicators}} = \textbf{\textit{Inventory Data}} * \textbf{\textit{Characterization Factor}} \quad \textbf{(2-1)}$$

Each LCI output result has an assigned characterization factor. Characterization of LCI data helps comparing different gases, chemicals, and other substances within each impact category.

2.1.4.5 *Normalization*

Fourth, in the Normalization step, the impact indicator data obtained from Characterization are divided by a reference value in order to compare the impact categories among the options in comparative LCA. Examples of reference values are: total resource use for a given area per capita basis, ratio of one alternative to the baseline, and the highest value among all options (United States Environmental Protection Agency, 2006b).

2.1.4.6 *Grouping*

Fifth, Grouping involves sorting or ranking indicators. Two possible ways to group impact indicators data are: (1) sort indicators by characteristics such as emissions or locations, and (2) sort indicators by a ranking system based on value choices (International Organization for Standardization, 1998).

2.1.4.7 *Weighting*

Next, the Weighting step can be undertaken. According to the EPA (2006), Weighting is the least developed stage of LCIA. If one alternative is clearly better than the other, i.e., the LCIA results are straightforward, weighting is not necessary (United States Environmental Protection Agency, 2006b). However, when evaluating alternatives with impact indicators results that are difficult to interpret and either decision has potential to cause different consequences, weighting is required in order to select the best alternative. Weighting consists of three steps: (1) identify the underlying values of stakeholders, (2) determine weights to place on impacts, and (3) apply weights to impact indicators. The Analytic Hierarchical Process (AHP), modified Delphi Technique, and Decision Analysis using Multi-Attribute Theory are the common tools that help the weighting process.

2.1.4.8 *Evaluation and Reporting*

Finally, the Evaluating and Reporting Results step can be completed. Some challenges of performing LCIA include consideration for the spatial and temporal system boundaries, and subjectivity issues in weighting (United States Environmental Protection Agency, 2006b). Other issues such as assumptions, known uncertainties, and simplifications made must be well documented.

2.1.4.9 *Available Software to Assist LCA*

The United States Environmental Protection Agency (2006b) reported 25 available software tools for conducting LCA studies. Some software tools have the ability to perform various LCIA method such as TRACI, CML 2001, Eco-indicator 99, Ecopoints 97, EDIP, EPS 2000, and IMPACT2002 (Martínez, Blanco, Jiménez, Saenz-Díez, & Sanz, 2015). Among the approaches reported by the United States Environmental Protection Agency (2006b), only a few software tools were designed to conduct LCAs for complex systems, such as buildings, and applicable for use in the U.S. Several software tools that are suitable for conducting building LCAs are described below.

BEES: Created by the National Institute for Standards and Technology (NIST) Building and Fire Research Laboratory, the BEES (Building for Environmental and Economic Sustainability) software tool can be used for balancing the environmental and economic performance of building products. The tool targets designers, builders, and product manufacturers, includes actual environmental and economic performance data for 200 building products (National Institute of Standards and Technology, 2010). One of the drawbacks of this LCA tool, though, is that the small number of building products in the database limits the ability to do a highly detailed LCA.

DuboCalc: The Netherlands Ministry of Transport, Public Works, and Water Management has created a software tool and database containing LCI data of construction materials which are used in civil works. Data included are secondary data, derived from other databases, brought together in a set to use with DuboCalc software for designers (Rijkswaterstaat, Royal HaskoningDHV, & Cenosco, n.d.).

The Impact Estimator: Developed by the Athena Institute, the Impact Estimator was prepared for architects, engineers, and researchers to get LCA answers about conceptual designs of new buildings or renovations to existing buildings. The Estimator assesses the environmental implications of industrial, institutional, office, or both multi-unit and single-family residential designs. The Estimator incorporates the Institute's inventory databases that cover more than 90 structural and envelope materials. Released in 2002, it simulates over 1,000 different assembly combinations and is capable of modeling 95 percent of the building stock in North America. Athena has also developed databases for energy use and related air emissions for on-site construction of building assemblies; maintenance, repair and replacement effects though the operating life; and, demolition and disposal (Athena Sustainable Materials Institute, 2016).

SimaPro: SimaPro is a professional LCA software tool that contains several impact assessment methods and several inventory databases, which can be edited and expanded. It can compare and analyze complex products with complex life cycles. This software is available to the research team and described in greater detail in the next section (Pre, 2016).

Since The United States Environmental Protection Agency reported this list in 2006, these tools and others have continued to develop. For example, BIRDS (Building Industry Reporting and Design for Sustainability) has been developed by NIST and contains a new database and software tools to assess three major determinants of building sustainability: energy, environmental, and cost performance. Moreover, BIRDS complements NIST's BEES tool, which allows a user to measure economic and environmental impacts of building products, ranging from concrete to roof coverings to floor coverings (US Department of Commerce, 2014).

2.1.4.10 *SimaPro*

SimaPro was developed 25 years ago by PRé Sustainability (in The Netherlands), and has become the most used LCA software (Pre, 2016). The software incorporates various LCI databases, including ecoinvent, Agri-footprint, ELCD, US LCI, Swiss Input/Output Database, LCA Food, The Social Hotspots Database, US Input/Output database, and European and Danish Input/Output Database. SimaPro applies a variety of well-developed methods to assess environmental and human health impacts. These methods include:

- BEES+ (National Institute of Standards and Technology, 2010)
- Water Scarcity (Berger, van der Ent, Eisner, Bach, & Finkbeiner, 2014)
- Human Health (Boulay, Bulle, Bayart, Deschênes, & Margni, 2011)
- Water Scarcity (Boulay et al., 2011)
- CML-IA (CML-Department of Industrial Ecology, 2016)
- Cumulative Energy Demand (Frischknecht et al., 2007)
- Cumulative Exergy Demand (Boesch, Hellweg, Huijbregts, & Frischknecht, 2007)
- Ecological Footprint
- Ecological Scarcity 2006 (Water Scarcity)
- Ecological Scarcity 2013
- Ecosystem Damage Potential
- EDIP 2003
- EPD 2013
- EPS 2000
- Greenhouse Gas Protocol
- Water Scarcity (Jefferies et al., 2012)

- ILCD 2011
- IMPACT 2002+
- IPCC 2013
- Human Health (Motoshita, Itsubo, & Inaba, 2010)
- Eco-indicator 99 (Berger et al., 2014; Pfister, Koehler, & Hellweg, 2009)
- Water Scarcity (Pfister et al., 2009)
- ReCiPe (Ridoutt & Pfister, 2010)
- ReCiPe Endpoint
- ReCiPe Midpoint
- TRACI 2.1
- USEtox

The significant advantage of SimaPro compared to other LCA software is the ability for collaboration among several users by allowing them to work on the same project simultaneously in one shared central database.

2.1.5 LCA Findings

2.1.5.1 *LCA for Building Energy Use in the U.S.*

According to the International Energy Agency (IEA), buildings are the largest contributors to energy consumption worldwide (International Energy Agency, 2013). The energy consumed by the building sector accounts for over one-third of total final energy consumption, and are an equally important source of carbon dioxide (CO_2) emissions (International Energy Agency (IEA), 2013). Also, according to the IEA (2013), the U.S. building construction industry should set the highest priority for advanced envelope technology, such as highly insulating windows and air sealing and insulation in cold climates. They also support a policy of deep renovation of existing buildings using a systems approach for implementing advanced envelopes and high-performance equipment. The second priority for the U.S. includes use of heat pumps for water and space heating and cooling, and the construction of new, zero-energy buildings by developing advanced holistic building design strategies with integrated renewable energy (International Energy Agency, 2013).

The building sector is grouped into two sub-sectors: residential and service. The service sub-sector includes activities related to trade, finance, real estate, public administration, health, food and lodging, education, and commercial services (International Energy Agency, 2013).

Commercial buildings account for about 46% of U.S. building energy consumption (United States Department of Energy, 2011). A total of 76.8% of this consumption is in the form of electricity (United States Department of Energy, 2011). The DOE (2011) predicted that the annual growth rate of commercial energy consumption is expected to reach up to 0.71%. Retail and office buildings are the most energy intensive in the U.S., accounting for 19% and 23% of total energy consumption in the commercial sector, respectively (Allouhi et al., 2015). HVAC systems are the highest energy consuming systems in commercial buildings; space heating and cooling consumed 31.3% of site energy in the commercial sector in 2015, followed by lighting at 11.4% (United States Department of Energy, 2011).

2.1.5.2 *LCA Findings for Building Structures*

In addition to building energy studies, past work has investigated the composition of building structures and materials for environmental impact evaluation. An LCA study of a 222 m^2 building and garage in Spain (Zabalza Bribián et al., 2009a), concluded that increasing insulation (expanded polystyrene) thickness by 10 cm could significantly reduce the energy load, as the building materials can reduce more than 60% of the heating consumption. In addition, it was found that replacing the conventional boiler with condensing boiler and removing the lower ground floor or garage would also increase energy savings. GHG reductions were predicted to reach 12.6 tons over the life cycle of the building through redesign, according to the same study. Through this study, future LCA studies for buildings need to investigate the structural details and insulation features of the buildings in order to capture accurate energy savings.

Materials used for building structural components also play an important role in defining life cycle environmental impacts. In particular, material-intensive features such as framing has been considered in prior studies. The cradle-to-grave life cycle impacts of borate-treated lumber framing and galvanized steel framing have been investigated (Bolin & Smith, 2011). Borate-treated lumber may be used for framing buildings in locations of high decay or termite hazard. The results indicated that borate-treated lumber framing can reduce life cycle impacts more than galvanized steel framing, including approximately four times less fossil fuel use, 1.8 times less GHG emissions, 83 times less water use, 3.5 times less acidification, 2.5 times less eco-toxicity, 2.8 times less smog formation, and 3.3 times less eutrophication.

Another study (Yu, Tan, & Ruan, 2011) concluded that the use of recycled-content materials provides an opportunity for reducing energy use and carbon emissions associated with the raw materials extraction phase of the life cycle, in addition to lower carbon emissions and energy use during the construction phase. Recycled building materials can include metals, concrete, masonry, ceramic tile, acoustic tile, carpet, and insulation. This study also compared the use of bamboo structure (bamboo columns or beams with steel joist) versus conventional brick-concrete buildings. According to the authors, bamboo has high strength and environmental-friendly characteristics such as renewable, biodegradable, and sequestering carbon. Three scenarios analyzing the benefits of reusing materials, materials recycling, and combustion of biomass associated with bamboo-structure buildings were also included. The data obtained was from conventional buildings in China and a prototype bamboo-structure building based on LEED standards. The results indicate that there is a potential to reduce embodied energy by 11.0% and carbon emissions by 18.5% by using recycled-content building materials. Reductions of 51.3% of total embodied energy and 69.2% of total embodied carbon can be obtained by recycling construction and demolition of bamboo-structure waste. While bamboo may not be a potential building material at the current time in the state of Oregon, this material or other similar materials may gain interest in the future and the over concepts presented in this study are worth noting for this report.

Van Ooteghem and Xu (2012) conducted a study on LCA of a single-story retail building in Toronto, Canada. In this study, five building models were analyzed: (1) conventional hot-rolled steel structure, (2) heavy timber structure, (3) structure with pre-engineered steel components designed and built off-site, (4) using steel components wherever possible, and (5) using wood components wherever possible. Types (4) and (5) mainly had different wall and roof materials but were based on the same structural system of types (1) and (2). The study found that commercial seam steel roofs had a high embodied energy. In addition, the type (3) structure showed the lowest total energy consumption and global warming potential of all five building models.

A sustainability assessment of flooring systems in Tehran was conducted using the analytic hierarchy process (AHP) along with LCA provides insights into three types of block joisted flooring systems: concrete, clay, and expanded polystyrene (EPS). The analysis showed that EPS block was the most sustainable solution when considering environmental, economic, and social impacts (Reza, Sadiq, & Hewage, 2011). The LCI inputs included energy, water, and raw materials. LCI outputs included waterborne, airborne, and solid wastes impacts. The environmental indicators used in the study included resource depletion, wastes and emissions, waste management, climate change, environmental risks, embodied energy, and energy loss. AHP was used to assist the decision-making efforts after weighting of environmental indicators. AHP was also applied to the economics and social impacts analysis. The study showed an attempt to overcome inaccuracy due to subjectivity of the Life Cycle Impact Assessment (LCIA) process by applying AHP.

Roofing and flooring structures were found to produce significant energy savings in a comparative LCA on a case study house (Islam, Jollands, Setunge, Haque, & Bhuiyan, 2015), called Base House, with eight modified alternative roofing and four floor designs being reported. A total of 12 variant houses were generated. AccuRate, a tool commonly used for star rating (Green Building Council of Australia, n.d.) in the Australian building industry, was used to select the chosen roofing and floor assemblage designs. The modified designs were chosen to be compliant with building code Australia (BCA) guidelines. The roofing or floor designs were varied so that the building achieves a chosen star rating from 3.6 to 4.4 stars. The two design options presented below produced the overall lowest impacts.

Skillion (Mono-pitched) Flat Roof (3.9 star rating):

- Roofing Material:

- Steel metal roof (2mm)
- Air gap (40mm)
- Sarking (reflective foil laminate)
- Cellulose fiber (loose fill): R3
- Ceiling Material:
- Extruded polystyrene: R3
- Softwood ceiling joists
- Glass fiber batt: R2
- Plasterboard

Mixed Floor (4.4 star rating):

- Ground floor (dining and living)
- Ceramic tiles
- Plywood (12 mm)
- Glass fiber batt: R1.0
- Vapor barrier
- Concrete slab: 2400 kg/m^3
- Ground floor (wet area and kitchen):
- Ceramic tiles
- Plywood (12 mm)
- Vapor barrier
- Concrete slab: 2400 kg/m^3
- Upper floor (bedroom, veranda, corridor):
- Tongue and groove timber board pine
- Plywood (12 mm)

- Glass fiber batt: R1.5
- Floor bearers, joists
- Plaster board
- Upper floor (wet areas)
- Ceramic tiles (8 mm)
- Vapor barrier
- Plywood (12 mm)
- Floor bearers, joists
- Plaster board

Despite the above positive findings, an LCA study of building GHG emissions in Finland indicated that new construction projects still caused a significant spike of emissions, and that the benefits of improved energy efficiency were realized after several decades when compared to renovating the old building stock or using existing residential buildings (Säynäjoki et al., 2012). The energy consumption of the base case buildings was based on the 2008 Finnish National Building Code (NBC), which is 100 kWh/m^2. The model incorporates the carbon emission reduction goal of 45 g-CO_2/kWh by the year 2060. The NBC buildings were compared with existing buildings that were built during the 1980s with energy consumption of 195 kWh/m^2 due to improved energy efficiency features, and buildings that were renovated during the 1960s with energy consumption of 50 kWh/m^2. Two new types of energy efficient buildings – "low energy" buildings which consumed 50 kWh/m^2 for heating and cooling, and "passive house" buildings which consumed 15 kWh/m^2 – were also included for comparison.

The results showed the cumulative carbon emissions of the buildings renovated in the 1960s were the lowest, when considering 50-year building life (Säynäjoki et al., 2012). Among the new buildings (NBC, low energy, and passive house), the passive house buildings produced the lowest cumulative carbon emissions due to the low energy consumption during the use phase. The authors suggested that if new energy efficient buildings initiatives were to be implemented, passive house buildings would be the best option. The high relative share of construction phase impacts was mainly due to the extensive inclusion of upstream production stages, the relatively strict building energy codes in Finland, and the inclusion of infrastructure development. The high energy performance and requirements of the buildings raise the relative significance of the construction phase emissions, as the construction of energy efficient buildings causes more short-term GHG emissions spike than conventional buildings, which can interfere with current GHG reduction goals (Säynäjoki et al., 2012). Thus, a comprehensive life cycle view of building environmental impacts is warranted.

Another study raised the issues with the true energy savings reportedly associated with current buildings certifications. An LCA was done on The Center for Sustainable Landscapes (CSL) office in Pittsburgh, PA, USA to evaluate life cycle environmental impacts (Thiel et al., 2013). The CSL office is a three-story, 24,350 ft^2 educational, research, and administrative office, and was compared with a standard commercial office building. CSL is a net-zero energy building and is designed to meet Living Building Challenge (LBC) criteria. The study found that the highest production-related environmental impacts were from concrete, structural steel, photovoltaic (PV) panels, inverters, and gravel. The CSL building exhibited 10% larger global warming potential and a nearly equal embodied energy per square foot than the comparative standard office building, largely due to the PV system. However, it was noted that the environmental impacts associated with the use phase of the net-zero energy building were expected to be very low relative to standard structures. The study indicated the need for future longitudinal studies to comprehensively capture this energy saving load.

2.1.5.3 *LCA Findings for HVAC and Lighting Systems*

Twelve building types (i.e., three and six-story dormitories; a fifteen-story hotel; three and six-story apartments; one and two-story schools; three, eight, and sixteen-story office buildings; a one-story restaurant; and a one-story retail store) were compared to evaluate energy use and carbon emissions (Kneifel, 2010a). The study used an average operational energy consumption of 3.414 MBtu/hr. (1MW), LCI data for CO_2, SO_2, and CO_2 from eGRID 2007 (United States Environmental Protection Agency, 2006a), and other electricity emissions data from BEES 4.0 (National Institute of Standards and Technology, 2010). The study found that increasing the energy efficiency of a building beyond the ASHRAE (American Society of Heating, Refrigerating, and Air-Conditioning Engineers) standard reduced annual energy use by 3.2-44.2%, depending on the building type. Design improvements focused on windows, insulation material and thickness, and HVAC systems. Carbon emissions reductions are highest (25%) for cities that have a combination of energy use reduction requirements, and electricity consumption based on at least 35% coal-fired generation. The findings also indicated the need for the HVAC system to be appropriately sized based on building heating and cooling loads to accurately capture the energy savings from smaller-size HVAC systems.

Approximately 30–50% of heating and cooling energy is lost through ventilation and air infiltration (Omer, 2008). Phase change material has been found to be the potential solution to overcome this issue. Phase change material (PCM) has the capability of storing thermal energy and therefore has seen increasing applications in various renewable energy technologies (Kenisarin & Mahkamov, 2007). Double skin facade ventilation systems can absorb solar radiation during the winter and prevent overheating during warm periods, which can lead to efficiently reduce HVAC energy consumption (Shameri, Alghoul, Sopian, Zain, & Elayeb, 2011). The use of ventilated double skin facades to reduce building energy demand and environmental impact during its operational phase has grown significantly; however, the system has been found to produce high environmental impacts during the manufacturing and dismantling phases (de Gracia, Navarro, Castell, Boer, & Cabeza, 2014). De Gracia et al. (2014) conducted a comparative LCA for a case study building that had ventilated double skin facades with

PCM. The results of the LCA showed, when considering a lifetime of 50 years, the use of this particular ventilated facade reduced the overall environmental impact of the building by 7.5%. In addition, other systems which use PCM in the building envelopes yielded significantly higher environmental payback compared to 31 years for the case of building with ventilated double skin facades with PCM. Replacing structural steel with wooden structure was found to further reduce environmental payback, as structural steel constituted over 60% of environmental impacts during manufacturing and dismantling phases due to its associated construction and disposal process.

Omer (2008) summarized strategies used to improve heating and cooling energy efficiency in buildings:

Strategies to improve building heating energy efficiency:

- Solar collection: collection of the sun's heat through the building envelope;
- Heat storage: storage of the heat in the mass of the walls and floors;
- Heat distribution: distribution of collected heat to the different spaces, which require heating;
- Heat conservation: retention of heat within the building.

Strategies to improve building cooling energy efficiency:

- Solar control: protection of the building from direct solar radiation;
- Ventilation: expelling and replacing unwanted hot air;
- Internal gains minimization: reducing heat from occupants, equipment and artificial lighting;
- External gains avoidance: protection from unwanted heat by infiltration or conduction through the envelope (hot climates);
- Natural cooling: improving natural ventilation by acting on the external air (hot climates)

Lighting systems have been shown to require significant energy inputs especially during the use phase of buildings. An LCA on light-emitting diode (LED) and high-pressure sodium (HPS) lighting found that due to the lower energy use and improved luminous efficacy, LED lighting reduces impacts by 41% when compared to HPS lighting (Tähkämö & Halonen, 2015). Furthermore, another study by Principi and Fioretti (2014) also showed a reduction of at least 41% of GHG and cumulative energy demands by using LED instead of compact fluorescent (CFL) lights for the purpose of lighting for offices. This study used 1 luminous flux (1 lumen/50,000 hours) and 1 lux/50,000 hours (to measure illuminance) as functional units. The illuminance produced by the two light

systems was analyzed using a room with internal dimensions of
4.30 m × 3.40 m × 2.70 m.

Strategies for reducing lighting energy use include (Omer, 2008):

- Penetration: collection of natural light inside the building;
- Distribution: homogeneous spreading of light into the spaces or focusing;
- Protect: reducing by external shading devices the sun's ray's penetration into the building;
- Control: control light penetration by movable screens to avoid discomfort.

The foregoing discussion has focused on the impacts of energy and material consumption. Strategies for improving the environmental impacts of energy generation also have been investigated, as discussed below.

2.1.5.4 *LCA Findings for Power Generating Systems*

2.1.5.4.1 Solar Power Systems

A full LCA was conducted investigating the embodied energy and emissions of solar thermal collector for sanitary warm water demand (Ardente, Beccali, Cellura, & Lo Brano, 2005). The life cycle phases of solar thermal collectors consist of production and delivery of energy and raw materials, production process, installation, maintenance, disposal, and transport during each step. The FU is one solar thermal collector with dimensions 2.005×1.165×0.91 m and a total net surface of 2.13 m^2. The FU was constituted of three main components: the absorbing collector (including the main framework, the absorbing plate and the pipes for the thermal fluid flow), the water tank (including the heat exchanger, the cover, the electrical resistor, and the inner pipes for the sanitary water flow), and the external support (employed to fasten the system on the house roof). The study concluded the total energy required over the life cycle of one solar panel is approximately 11.5 GJ, and total CO_2 emissions are approximately 650 kg CO_2/panel. The study also emphasized the importance of employing uncertainty and variability analysis to capture worst case scenarios.

Prior work (Al-Sulaiman, Hamdullahpur, & Dincer, 2012) assessed the efficiency, net electrical power, and electrical to heating and cooling ratios of a system using parabolic trough solar collectors and organic Rankine cycle for combined cooling, heating, and power production. In this system, a heat exchanger is used for waste heating. The other portion of waste heat is used for cooling through a single-effect absorption chiller. The study compared three modes of operation: a solar mode characterized by a low-solar radiation, a solar and storage mode characterized by a high-solar radiation, and a storage mode characterized by the operation of the system at night time through a thermal storage tank subsystem. The system was designed to produce 500 kW of electricity. The solar mode was shown to have the highest efficiencies (15% for electrical efficiency and 94% for electrical efficiency using combined cooling, heating, and power production system).

A comparative LCA among three different solar energy storage systems - sensible heat storage in solid (high temperature concrete) storage media, sensible heat storage in liquid (molten salts) thermal storage media, and latent heat storage which used phase change material (PCM) (Oró, Gil, de Gracia, Boer, & Cabeza, 2012) found that the system based on solid media (high temperature concrete) showed the lowest environmental impact per kWh. The solid media thermal storage system has a storage capacity of about 350 kWh and can operate with maximum temperatures of 390 °C, with a tubular heat exchanger integrated into the storage material. The system consists of two modules with dimensions of 0.48 × 0.48 × 23 m. The design's simplicity of solid media system mainly contributed to the lowest environmental impacts. On the other hand, the liquid media (molten salts) system showed the highest impact per kWh stored because it needed more material and equipment during operation phase. This study investigated the energy savings related to the stored energy of the different systems to balance the environmental impact produced during the manufacturing and operation phase.

2.1.5.4.2 Geothermal and Hybrid Systems

According to the U.S. DOE (Nathwani, J., & National Renewable Energy Laboratory (U.S.), 2004), there are three primary ways geothermal energy can be applied: electricity production, direct-use applications, and heating and cooling buildings with geothermal heat pumps. In particular, in the direct use application, hot water from geothermal resources can be used to provide heat. A well is drilled into a geothermal reservoir to provide a steady stream of hot water. The water is brought up through the well, and a mechanical system of piping and pumps, a heat exchanger, and controls delivers the heat directly for its intended use. Today, most geothermal direct-use applications circulate these fluids through closed-loop, emissions-free systems. For heating and cooling, geothermal heat pumps (GHPs) use the shallow ground, which maintains a nearly constant temperature between 50° and 60°F (10°–16°C), as an energy storage sink. GHPs transfer heat from a building to the ground during the cooling season, and transfer heat from the ground into a building during the heating season. GHPs marketed today also can provide hot water (Nathwani, J., & National Renewable Energy Laboratory (U.S.), 2004).

A recent study (Russo, Anifantis, Verdiani, & Mugnozza, 2014) totaled the primary energy demand of a conventional hot air generator using liquefied petroleum gas (LPG-HG) as 1.223 MJ. The main energy load was allocated to the operation phase (1.187 MJ). The Photovoltaic-Geothermal Heat Pump (PV-GHP) integrated system, on the other hand, consumed no energy during the operation phase. This made the total primary energy demand equal to approximately 0.622 MJ for the entire life cycle. GHG emissions of an LPG-HG system was found to be 8.725×10^{-2} kg CO_2 eq., versus 6.344×10^{-2} for the PV-GHP system.

Another study (Koroneos & Tsarouhis, 2012) revealed that the use of solar cooling had the highest environmental impact due to the manufacturing of solar panels. This study included exergy analysis and the LCA of three solar systems - space heating, space cooling, and hot domestic water production. A PV system was also used for electricity production and added to the comparison of environmental impacts. The existing geothermal field was utilized via heat pumps for hot water system and was included in the analysis of water heating system. The functional unit used in the calculations was kg emission(s) per kWh. SimaPro and GaBi LCA software were used. The results of exergy efficiency analysis indicated solar cooling system had the highest exergy efficiency due to higher exergy efficiencies of solar collectors (83.3%) and solar heat exchanger systems (9.59%) used for cooling. Domestic hot water was second to solar cooling system with regards to exergy efficiency due to the contribution of the geothermal heat exchanger (42% exergy efficiency). However, solar cooling produced the most kg/kWh emissions outputs, followed by solar heating, water heating, and power generating using PV system.

In the domain of large building sectors, the hotel sector represents a concentrated energy consuming entity that creates one of the largest negative environmental impacts. Important factors such as stakeholders' opinions, building codes, availability of design alternatives, and project management plans can influence the selection of alternative designs for energy supply systems and should be included in the analysis. A case study by Ayoub, Musharavati, Pokharel, and Gabbar (2015) on a hybrid energy supply system (HESS) consists of PV panels, wind turbines, and conventional electricity through the grid was used to demonstrate the application of a proposed risk based life cycle assessment (RBLCA) using IDEF-0 in order to integrate the required activities surrounding the selection of alternative energy supply systems. RBLCA was composed of three main stages: (1) establish the life cycle stages model, (2) perform risk assessment, and (3) manage risks through the building life cycle stages.

During the first stage, LCA was performed, with constraint inputs such as energy consumption data, vanadium redox battery's energy and emission data (for PV panels and wind turbines), available green materials, project management plan, ASHRAE 90.1-2007 building code from stakeholders and project management team. Potential risks derived from LCA study and risks associated with activities from the Work Breakdown Schedule (WBS) were prioritized and analyzed during the second stage, risk assessment. Risk assessment stage involved four steps: qualitative risk analysis, quantitative risk analysis, risk characterization, and setting risk indicators. The primary environmental impact categories for the study were fossil fuel depletion and climate change potential. The Relative Importance Index (RII) was used to help identify the risk indicators, i.e., risks that require immediate response. In the final stage, risk scenarios were developed to plan risk responses, control risks, and update the existing risk management plan.

Ayoub et al. (2015) found that the primary energy consumed in electricity production is mainly due to processing of the natural gas and related electricity production (91.5%), followed by natural gas extraction and transmission (5.04%). All other processes represent less than 4% of primary energy consumption. The climate change potential shows a similar pattern of equivalent CO_2 emissions where natural gas processing and electricity production accounted for 80.90% of the total emissions. Gas extraction and transmission accounted for almost 6% of total equivalent CO_2 emissions. Other environmental emissions from the HESS are SO_x (598.50 g/m^2/yr.) and NO_x (91.90 g/m^2/yr.). This result indicated that the HESS did not meet the ASHRAE standard requirement for green building certification. All risks derived from the second stage are grouped in five components: social, environmental, health, technical, and operational and policy. From results of RII and probability of occurrence, the risks that should be addressed by decision makers based on this study are noise risks, high emissions, and business risk of using high share of renewable energies. The same study also found that increasing renewable energy use will decrease climate change and fossil fuel depletion impacts.

In the same study, Ayoub et al. (2015) found that the result of the energy consumed to produce one MWh of wind-electricity were higher than that of PV solar electricity (1037.93 MJ/MWh and 1011.47 MJ/MWh respectively). The major energy consumed was in system installation, wind turbines transportation, followed by the battery production; while the manufacturing process of wind turbines accounted for the lowest energy and emissions. The concrete used to construct the supports for the turbine (192.4 ton/turbine) accounted for most of the energy consumed in system installation. CO_2 emissions in the system installation showed the same trend.

An LCA study of a community hydroelectric system in a rural village in Thailand concluded that smaller hydropower systems had greater environmental impact per kWh generated than larger systems. However, the hydropower system yielded better environmental and financial outcomes than diesel generator and grid connection alternatives for electricity use in the same location (Pascale, Urmee, & Moore, 2011). Another comparative LCA study done on three electricity generating systems – diesel, PV, and wind hybrid micro-grid in Thailand found that the wind hybrid micro-grid system has the lowest GHG emissions and abiotic resource depletion potential. The impacts of home diesel generators were the highest among all three systems (Smith et al., 2015).

2.2 LIFE CYCLE COST ANALYSIS

To holistically evaluate the benefits of buildings projects, economics analysis is required. The benefits of buildings, particularly energy-efficient buildings, are not often recognized until later periods in the life of the buildings. Therefore, a life cycle approach is needed to capture the cumulative benefits to be evaluated against the upfront investment costs. Life Cycle Cost Analysis (LCCA) is chosen to be among the most common methods to perform life cycle economics analysis.

2.2.1 Overview of Life Cycle Cost Analysis:

LCCA is "an economic method of project evaluation in which all costs arising from owning, operating, maintaining, and ultimately disposing of a product or system are considered to be potentially important to that decision" (S. Fuller & Petersen, 1995). A key advantage of LCCA is in the evaluation of design alternatives that satisfy a set of performance requirements, especially when the cost and benefits cannot be directly estimated, such as in the case of cost-effective energy conservation projects. These performance requirements can also include intangible benefits, such as occupant comfort, safety, adherence to building codes, and system reliability. Two of the most notable techniques used in LCCA that are different from the traditional economic payback method are the savings-to-investment ratio (SIR) and adjusted internal rate of return (AIRR) approaches. LCCA focuses on the future savings by using discounted cash flow, constant versus current dollars, and price escalation rates.

2.2.2 LCCA for Buildings

Energy conservation projects are known to have higher initial capital cost (S. Fuller & Petersen, 1995). The rise of energy conservation projects makes LCCA an effective way for evaluating new design alternatives or selecting projects for improvements of existing components on an energy cost basis.

2.2.2.1 *Relevant Resources*

Other resources are helpful in providing more in-depth details on certain methods for performing specific economic analyses on buildings and building systems. ASTM International has published standards on building economics and life cycle costing (LCC) in its annual ASTM Volume 04.11 Building Constructions (American Society for Testing and Materials (ASTM), 2015). Standards related to LCCA contained in this volume include:

- E917 – Standard Practice for Measuring LCC of Buildings and Building Systems (ASTM International, 2015a).
- E964 – Practice for Measuring Benefit-to-Cost and Savings-to-Investment Ratios for Buildings and Building Systems (ASTM International, 2015b).
- E1057 – Practice for Measuring Internal Rate and Adjusted Internal Rate of Return for Investments in Buildings and Building Systems (ASTM International, 2015c).
- E1074 – Practice for Measuring Net Benefits for Investments in Buildings and Building Systems (ASTM International, 2012a).
- E1121 – Standard Practice for Measuring Payback for Investments in Building and Building Systems (ASTM International, 2015d).

- E1185 Standard Guide for Selecting Economic Methods for Evaluating Investments in Buildings and Building Systems (ASTM International, 2015e)

- E1369 - Guide for Selecting Techniques for Treating Uncertainty and Risk in the Economic Evaluation of Buildings and Building Systems (ASTM International, 2015f).

- E1765 - Practice for Applying Analytical Hierarchy Process (AHP) to Multi-attribute Decision Analysis of Investments Related to Buildings and Building Systems (ASTM International, 2011a).

- E1946 - Practice for Measuring Cost Risk of Buildings and Building Systems and Other Constructed Projects (ASTM International, 2012b).

- E2204 - Guide for Summarizing the Economic Impacts of Building-Related Projects (ASTM International, 2012c).

2.2.2.2 *Phases of a Building LCCA*

An LCCA building project usually follows a multi-step process to evaluate the drivers of cost over the life of the project. LCCA generally consists of the following steps: project description, alternatives identification, relevant parameters establishment, cost data and related factors estimation, computation and comparison, interpretations, intangibles description, recommendations, and conclusion. A general format of building LCCA (S. Fuller & Petersen, 1995) is provided below, together with descriptions of each step.

2.2.2.2.1 Project Description

General Information - General information related to building system being considered, which can include building types, activities within, occupant usage, and comfort requirements. Types of energy system such as HVAC and building energy usage should also be listed.

Type of decision to be made – There are five main decision types to be made when doing an LCCA for a project. These decision types include: (1) accept/reject an alternative based on economic measures, (2) select an alternative with optimal efficiency, (3) select optimal system type, (4) select a combination of interdependent systems, (5) ranking independent projects. Details on decision types are provided in Section 2.2.2.3.

Constraints – Technical criteria, budget allowance, and desired features, together with regulatory constraints should be considered while evaluating candidate alternatives. Technical constraints can include a set of physical (e.g., available technology based on locations), functional, or safety-related technical requirements. An example of desired features can be the building's preserved historic features. Regulatory constraints such as building codes and safety codes can mainly affect the costs associated with the projects. CSI's MasterFormat

Division 01 – General requirements (CSI, 2014a) provide a list of common requirements to be considered during the planning phase of construction projects.

2.2.2.2.2 Alternatives

Technical Description – Technically sound and practical alternatives can be identified after considering all requirements listed above. Practical alternatives must not only satisfy the technical requirements but also be comfort-compatible, user-friendly, safe, and allow for occupants' productivity and design aesthetics.

Rationale for Inclusion – Projects that are not practical to implement or do not meet the technical requirements should not be included further in the analysis. However, some alternatives offer benefits that are difficult to capture in dollar terms but have values unique to investors or a group of stakeholders should be included for analysis.

Non-monetary Considerations – Occupants and investors' desired features such as design aesthetics, preserved historic values, and occupants' comfort should be added for fair comparison across all feasible alternatives.

2.2.2.2.3 Common Parameters

Study period – The time over which the costs and benefits related to the investment decision is of interest to the relevant stakeholders. The same study period needs to be applied to all the alternatives being considered.

Base date – The point in time all project-related costs are discounted to.

Service date – The date on which operating and maintenance costs are expected to incur and not before.

Department of Energy (DOE) discount rate vs. Office of Management Budget (OMB) discount rate

Treatment of inflation – constant dollars discount with real discount rate (excluding rate of inflation) vs. current dollars discount with nominal discount rate (including rate of inflation). The U.S. DOE prefers the constant dollar method (S. Fuller & Petersen, 1995).

Operational assumptions, energy, and water price schedules.

2.2.2.2.4 Cost Data and Related Factors - Section 2.2.3.2

Investment-related Costs

Operating-related Costs

Energy Usage Amounts (By Type): Local energy at building site and DOE-projected energy price changes are used to calculate annual energy costs for each type

Water Usage and Disposal Amounts: 0% differential price change unless justified

Timing of Costs

Cost Data Sources

Uncertainty Assessment: Sensitivity analysis

2.2.2.2.5 Computations – Section 2.2.3

Discounting: Present value at the base date

Computations of LCC

Computations of Supplementary Measures

2.2.2.2.6 Interpretation

Results of LCC Comparisons: lowest LCC, highest net savings, SIR>1, AIRR>FEMP (Federal Energy Management Program) discount rate

Uncertainty Assessment

Results of Sensitivity Analysis

Additional results and conclusion of an LCCA can include the following sections:

Non-Monetary Savings or Costs: Description of Intangibles

Other Considerations

Recommendations

2.2.2.3 *Decision Making Types*

There are five decision types that need to be defined prior to performing an LCCA. These decision types (S. Fuller & Petersen, 1995) include:

Accept/Reject an alternative based on economic measures: This decision type refers to evaluating only one building project's cost effectiveness. The final decision is whether or not to undertake the project.

Select Optimal Efficiency Alternative: This involves analyzing the level of efficiency that minimizes LCC or maximizes NS. The alternatives considered can be energy, water, or other performance of interest. The objective is to determine which of the available efficiency levels is the most cost effective for the application being considered. Efficiency level includes a given set of performance requirements that can be achieved with different amounts of resource input, e.g., energy or water.

Select Optimal System Type: Similar to selecting optimal efficiency alternative, this refers to the problem of selecting the most cost-effective system type, e.g., HVAC system or wall construction type, for a particular application.

Select a Combination of Interdependent Systems: Building system interactions most likely impact energy savings include HVAC, thermal integrity of overall building envelope, and lighting system efficiency and usage. This requires simultaneous energy analysis to properly account for the interaction among the systems. This decision type deals with analyzing the cost-effectiveness of a combination of systems instead of separate systems.

Ranking Independent Projects: This is fundamentally different from the above four types in the way that only mutually exclusive projects are being considered. When funding is insufficient, not all identified projects can be implemented. LCCA is also effective at providing guidance for allocating funding to the most cost-effective subsets of projects.

2.2.3 LCCA Methodologies for Buildings

Common values of interest and descriptions of the input parameters are described below (S. Fuller & Petersen, 1995).

2.2.3.1 *Cost and Savings Accounting Methodologies*

The general model to calculate life cycle costs is as follows:

$$\boldsymbol{LCC = \sum_{t=0}^{N} \frac{C_t}{(1+d)^t}} \tag{2-2}$$

Where:

LCC = Total LCC in present-value (PV) dollars of a given alternative

C_t = Sum of all relevant costs (initial and future less positive cash flow) occurs in year t

N = Number of years in the study

d = Discount rate

For building-related projects, the formula for LCC can be stated as:

$$LCC = I + Repl - Res + E + W + OM\&R$$

(2-3)

Where:

I = Investment costs

Repl = Replacement costs of capital

Res = Residual value less disposal costs

E = Energy costs

W = Water costs

OM&R = Non-fuel operating, maintenance, and repair costs

Other criteria must also be considered along with the LCCA results for accurate interpretation. These criteria include net savings (NS), savings to investment ratio (SIR), adjusted internal rate of return (AIRR), and discounted payback (DPB) period. These criteria are summarized below.

Net Savings (NS) can be calculated as:

$$NS = LCC_{base\ case} - LCC_{alternative}$$

(2-4)

SIR is calculated as:

$$SIR_{A:BC} = \frac{\sum_{t=0}^{N} S_t/(1+d)^t}{\sum_{t=0}^{N} \Delta I_t/(1+d)^t}$$

(2-5)

Where:

SIRA:BC = Ratio of PV savings to additional PV investment costs of the mutually exclusive alternative

S_t = Savings in year t in operational costs attributable to the alternative

ΔI_t = Additional investment-related costs in year t attributional to the alternative

t = Year of occurrence (0 is base date)

d = Discount rate

N = Length of study

AIRR (to compare against MARR, i.e., discount rate) is calculated as:

$$\boldsymbol{AIRR = (1 + r)(SIR)^{1/N} - 1}$$

(2-6)

Where:

r is the reinvestment rate.

DPB (Discounted Payback) is the minimum number of years, y, for which

$$\sum_{t=1}^{y} \frac{\Delta E_t + \Delta W_t + \Delta OM\&R_t + \Delta Repl_t + \Delta Res_t}{(1 + d)^t} \geq \Delta I_0$$

(2-7)

Where:

ΔE_t = Savings in energy costs in year t

ΔW_t = Savings in water costs in year t

$\Delta OM\&R_t$ = Difference in OM&R costs in year t

$\Delta Repl_t$ = Difference in capital replacement costs in year t

ΔRes_t = Difference in residual value in year t

d = Discount rate

ΔI_0 = Additional initial investment cost

2.2.3.2 ***Cost Categories Considered***

Cost data allocation and organization are among the biggest challenges of performing an LCCA. The two main life cycle costs are investment-related costs and operational costs, and, thus, these categories are discussed in greater detail below. Within each category, costs can be sub-categorized into one-time cost, recurring cost, present cost, and future cost (Fuller & Petersen, 1995). These sub-categories of costs need to be identified to apply the correct calculating treatment.

2.2.3.2.1 Investment Related Costs

All acquisition costs such as costs related to planning, design, purchase, and construction, are investment-related costs. Also, residual costs such as resale, salvage, and disposal, as well as capital replacement costs are considered investment-related costs. Water and energy cost for the construction process belong to this category and can be allocated to the timeframe from base date to service date of the building.

For organization of investment-cost-related data, the U.S. DOE recommends using the UNIFORMAT II standard published by the U.S. Department of Commerce (DOC) (Charette & Marshall, 1999). The UNIFORMAT II standard for building elements and related site work can be used for classification of the costs related to the construction process.

2.2.3.2.2 Operational Costs

Costs that are paid from an annual operating budget and not from capital funds are considered OM&R (operating, maintenance, and repair) costs. OM&R activities begin on the service date and continue through the service period of the building.

U.S. DOE's discount rate can be used for energy discount rate besides MARR (minimum acceptable rate of return used in private sector) for federal building projects (Fuller & Peterson, 1995). Non-energy and water conservation and renewable resource projects can use OMB discount rates, which are determined by the life of the investment and who receives the benefits. As a type of recurring costs, energy costs can differ based on seasons (summer versus winter), time of use, block schedule, and demand. Therefore, each type of energy used by building or building systems need to be estimated. Computer simulation programs such as ASEAM, DOE-2, BLAST, and ESPRE can be used to estimate energy usage.

Current and local energy prices are to be used instead of national average price. These prices should be based on the base date and not the service date. In cases of energy-conservation building projects where unit prices vary with usage amounts (e.g., declining block-rate schedule), prices of last unit used in each billing period is the most appropriate. However, average unit price is appropriate when comparing two systems that use different fuel types.

Water costs are handled similarly to energy costs, except that there is no DOE discount rate for water and general rate of inflation is assumed instead (S. Fuller & Petersen, 1995). Two types of water costs, i.e., water usage and water disposal, may have their own unit costs. Water cost-savings during operational phase are also separated from investment-related water costs.

2.2.4 LCCA Findings

2.2.4.1 *Costs and Savings Accounting Methodologies*

Past researchers (Tsai, Yang, Chang, & Lee, 2014) performed LCCA on six types of green building projects using activity based costing (ABC) and "green" building concepts to select materials and energy systems that are suitable for each building type. ABC differs from conventional costing methods by distributing indirect cost focused on the activities. In the ABC method, resources are consumed by activities and activities are consumed by products. By using the ABC technique, more systemic and accurate results can be obtained. ABC also allows accounting for carbon and other environmental tax and tax savings over the building lifetime. Furthermore, integer programming was used to maximize potential paybacks by choosing the optimal number of cost drivers such as labors and material used. ABC was also used in other studies to select optimal systems for buildings (Waghmode, Sahasrabudhe, & Kulkarni, 2010). Target costing (setting maximum costs allowed on a product and still achieving desired profit margin) can also be combined with ABC to further control costs, as conventional cost systems become insufficient in providing accurate data to target costing (Pazarceviren & Dede, 2015).

Past research (Buys, Bendewald, & Tupper, 2011) provided an overview of how to perform LCCA, including non-conventional LCCA steps called "establishing the baseline" - defining the building design that minimally meets all of the owner's needs, and "bundling measures" - evaluating the synergistic benefits of measures in order to support integrative design and allow for more cost-effective measures to absorb the cost of measures that do not "pay for themselves," leading to a more efficient design with more non-quantitative benefits. Simple payback method may underestimate the value of energy-efficiency investment as it only accounts for annual energy cost savings and capital cost and ignores other significant costs and benefits (e.g., rebates, maintenance savings, avoided immediate and future capital investments) as well as savings that accrue beyond the timeframe of the simple payback period.

To account for dynamic cost changes throughout the construction project, researchers (Riggs & Jones, 1990) proposed a technique based on a graph-theoretic representation of interrelationships among the variables. These variables are functions making up of systems learning, cost parameters, cost factors, and quantities. A diagraph representation of relationships of variables affecting costs serves as the basis for establishing the network. Flow-graph theory methodology is used to solve the network.

Uncertainty is one of the most challenging issues when attempting to accurately estimate LCCs of buildings. Risks, such as accidents and project delays, are unknown factors and difficult to capture. LCCA methodologies that use simulation, e.g., Monte Carlo (Humphries Choptiany & Pelot, 2014a), has been used to capture uncertainties. Common thresholds used for policy decision making, such as ALARP (as low as reasonably practicable) and cost per accident type, also can be used to model expected costs based on current practice (Nam, Chang, Chang, Rhee, & Lee, 2011).

2.2.4.2 *Evaluation Techniques*

Stanford University Land and Buildings Guidelines for Life Cycle Cost Analysis proposed the Decision Matrix (DM) method (Figure 2.1). The guide quantifies up to 14 possible LCC comparisons organized into six general categories: Energy Systems, Mechanical Systems, Electrical Systems, Building Envelope, Siting/Massing, and Structural Systems. Within each category, design and system alternatives that address the same need are presented for comparison. The DM can help determine which of the six categories and 14 comparative analyses have the highest potential LCC benefit for the project. The vertical axis represents the potential cost impact to the project. The horizontal axis reflects the complexity of the analysis required. The six categories with 14 analyses are placed in one or more of the four quadrants. Those in Quadrant I (simple analysis with high potential cost impact) should have the highest priority, followed by Quadrant II which include studies that require complex analysis but have a high potential impact. Simple analyses with low potential impact would have the next prioritization (Quadrant III). Complex analyses with low potential impact (Quadrant IV) has the least priority (Stanford University Land and Buildings, 2005).

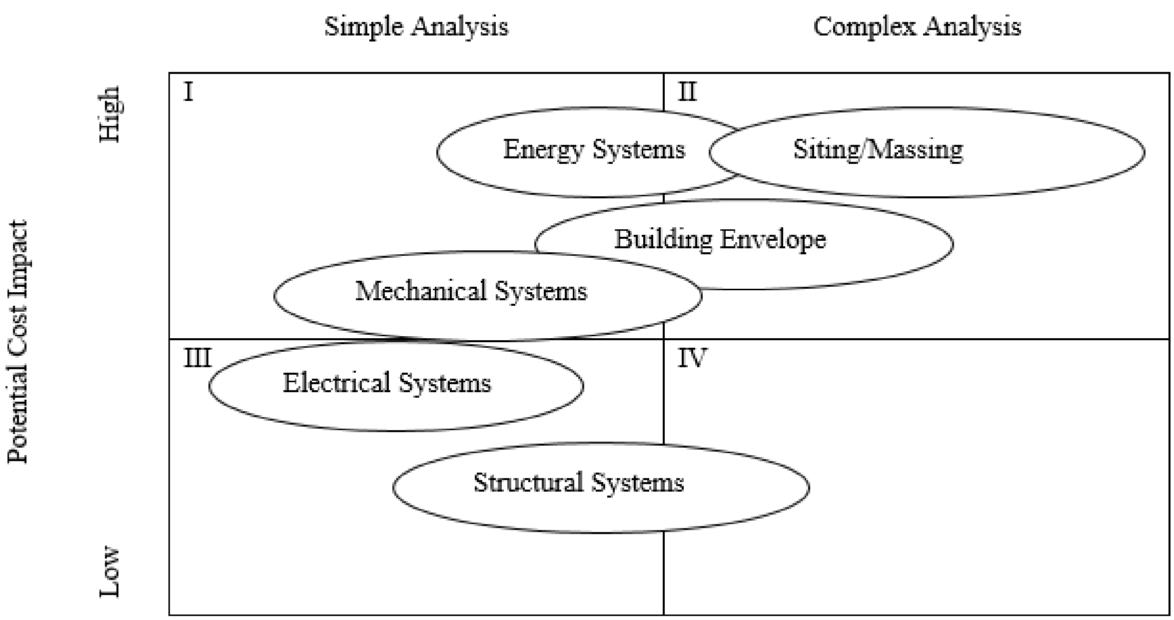


Figure 2.1. Stanford University land and buildings decision matrix for LCCA cost priorities (Stanford University Land and Buildings, 2005)

Another type of DM method was proposed (Humphries Choptiany & Pelot, 2014b). This study incorporated weights, threshold values, scoring, experts' opinions, and utility functions based on environmental, social, economic, and engineering requirements to aid the decision-making process. Four objectives were selected: minimizing expected environmental impacts, maximizing expected public support, minimizing expected cost, and maximizing expected engineering benefits. Within each objective, a hierarchy of sub-objectives (called criterion in the study) was also developed. Weights, maximum/ minimum acceptable limits (threshold values), experts' opinions, and utility functions based on past research's results, estimated distributions, and stakeholders' opinions were assigned to each criterion. Scorings for the criteria for alternative projects were computed. Mitigation options for each project alternative were proposed, and permutations of these mitigations were analyzed using decision tree to arrive at the final possible scores for each alternative. The authors acknowledged the disadvantage of using estimated distributions and simulation software instead of real data. However, the study went beyond evaluating the pre-set of objectives by incorporating actual mitigation techniques into the final evaluation.

In addition, a multi-criteria decision-making method for pavement project evaluation using LCCA was developed (Hevari & Esmaeeli, 2014). The study combined three approaches that (1) utilize fuzzy set theory to model and handle uncertainties; (2) consider the extra user costs attributable to inadequate pavement condition; and (3) consider life cycle pavement performance as a criterion that describes overall pavement serviceability condition. Fuzzy numbers are a generalization of the concept of interval of confidence and requires ranking. In the study, decisions were made based on stochastic optimization techniques based on updating risks and costs information that occurs during the project.

LCA results can be combined with costs of toxic risks, energy, and GHG emissions for remediation (Inoue & Katayama, 2011). The study focused on developing a two-scale evaluation concept that consists of two-dimension outputs for evaluation: risk-cost, risk-energy consumption, and risk-GHG emission.

2.2.5 Available Software to Assist LCCA

Building Life Cycle Cost-5 (BLCC-5) is a software that conducts economic analyses by evaluating the relative cost effectiveness of alternative buildings and building-related systems or components. It is also used to evaluate the costs and benefits of energy and water conservation as well as renewable energy projects. BLCC-5 also calculates comparative economic measures such as net savings, savings-to-investment ratio, adjusted internal rate of return, and years to payback (United States Department of Energy, n.d..-c). Appendix A presents the complete list of 39 tools and software provided by the DOE and other federal organizations to assist estimation of energy and water usages and costs.

2.3 REVIEW OF CURRENT SUSTAINABLE BUILDING CONSTRUCTION RATING SYSTEMS

Currently, in the U.S., there are different codes, standards, rating systems, and recommendations which have been developed to provide guidelines for sustainable building construction. Each of the standards or guidelines has a specific focus and approach to achieve the target of green building or sustainable construction. The International Green Construction Code (IgCC) and the California Green Building Standards Code are building codes used in some states in the U.S. However, neither of these codes is enforced in Oregon. ANSI/ASHRAE/IES Standard 90.1 focuses on the energy performance for non-residential building and high-rise residential buildings (ASHRAE, 2013). The Federal Green Construction Guide for Specifiers (FGCGS) is a detailed guideline developed based on ASTM standards, ASHRAE standards, Leadership in Energy and Environmental Design (LEED) v3, and other industrial standards (United States Environmental Protection Agency, 2010). FGCGS provides a comprehensive guideline for green building construction methods, especially for materials selection. In addition, rating systems such LEED v4, Green Globes, and the Living Building Challenge are also widely accepted in the U.S. (Green Building Initiative, n.d.; International Living Future Institute, 2016; United States Green Building Council, n.d.-b) These rating systems were developed based on current industrial standards and codes. Among the three rating systems, certifications of LEED v4 and Green Globes are awarded based on total points earned prior to and during construction. Since both LEED v4 and Green Globes use a point-rating system, it allows them to be adopted easily. LEED v4 was developed by U.S. Green Building Council (USGBC) and Green Globes was developed by Green Building Initiative (GBI). Both systems are highly valued and widely recognized, especially in North America. On the other hand, a Living Building Challenge certificate is only awarded after one year of monitored performance for the building. It is only awarded if the project meets the requisite Living Building Challenge standard (including net zero energy and net zero water usage).

FGCGS is a guidance document to provide guidelines and resources for achieving environmental goals set by federal agencies. LEED v4, Green Globes, and the Living Building Challenge are recognized in Pacific Northwest. Therefore, in the following sections, FGCGS and three rating systems are discussed and compared.

2.3.1 Federal Green Construction Guide for Specifiers (FGCGS)

According to FGCGS, there are five environmental goals for sustainable building: employing integrated design, optimizing energy performance, protecting and conserving water, enhancing indoor environmental quality and reducing the environmental impact of materials. To achieve these environmental goals, existing guidelines are used to provide specific guidance.

2.3.1.1 *Energy*

For optimizing energy performance, Executive Order (EO) 13423, EO 13514, Energy Policy Act of 2005, 10 CFR 435 – Energy Performance Standards for New Buildings and FAR Part 23, 48 CFR 23 – building equipment and light, Energy Star and Federal Energy Management Program (FEMP) are referred (United States Environmental Protection Agency, 2010). In FGCGS Section 01 92 00, operational energy is required to be monitored and recorded (United States Environmental Protection Agency, 2010). Portfolio Manager can be used to assist the tracking and assessing the energy consumptions. Energy Performance of the building needs to meet or exceed the requirement of ENERGY STAR (United States Environmental Protection Agency, 2010). For whole building energy use rating, EPA Target Finder can be used. Due to the need to reduce the annual energy consumption in federal buildings, green power is encouraged to be incorporated. The requirement of the use of green power in FGCGS is adopted from LEED v3 (United States Green Building Council, n.d.-a). In addition, requirements on solar energy power and wind power are specified in Section 48 14 00 and Section 48 15 00 respectively (United States Environmental Protection Agency, 2010).

2.3.1.2 *Materials*

For reducing the environmental impact of materials, EPA Comprehensive Procurement Guidelines, USDA Biopreferred, Federal Electronics Challenge and ISO 14001 or equivalent are referred (United States Environmental Protection Agency, 2010). FGCGS specifies the environmental requirements for products. Environmentally preferable products are suggested to be used in the project. In FGCGS Section 01 67 00, documentation requirements of related products are specified: 1) Affirmative Procurement Reporting Form; 2) Environmental data in accordance with Table 1 of ASTM E 2129 for specified products (list of the products can be found in Appendix B); 3) Material Safety Data Sheet (MSDS); 4) LCA for specified product (list of the products can be found in Appendix B); 5) Chain of Custody for wood products; and 6) Operating and Maintenance Manual Submittals (United States Environmental Protection Agency, 2010).

FGCGS specifies the requirement for building design life, building element design life, and building service life of the sustainable federal facilities. The specific requirements can be found in FGCGS Section 01 81 10 (United States Environmental Protection Agency, 2010). In addition, a general description of life-cycle cost can be found in Section 01 81 10: "first cost," such as design and construction expenditures account for 5-10% of total life-cycle costs; land acquisition, conceptual planning, renewal or revitalization accounts for 5-35%; operation and maintenance account for 60-85% (United States Environmental Protection Agency, 2010). FGCGS also specifies the requirements of selection of different materials. Many requirements are adopted from LEED v3 combined with executive orders, EPA policies and industrial standards. Therefore, the information can be useful for selecting alternative materials in LCA (United States Environmental Protection Agency, 2010).

2.3.2 LEED v4 Building Design and Construction (BD+C)

In the LEED v4 BD+C rating system (henceforth LEED v4), there are eight different categories and a total of 110 points possible to achieve increasing levels of LEED certification. Among these categories, Energy and Atmosphere (EA) and Materials Resources (MR) are two major focuses, of which EA takes 33 points and MR has 13 points (United States Green Building Council, 2018). The points needed for different certification levels are shown in Table .2.

Table 2.2. Total Points Needed for Different LEED Certification Levels

Certification Levels	Points Required
LEED Certified	40-49
LEED Silver	50-59
LEED Gold	60-79
LEED Platinum	80+

In addition, projects are categorized into different types, including new construction, core and shell, schools, retail, data centers, warehouses and distribution centers, hospitality, and healthcare. In this literature review, only the statements and requirements that are related to energy and materials and apply to new construction and core and shell are included.

2.3.2.1 *Energy*

2.3.2.1.1 Prerequisite

Among all three rating systems, LEED v4 is the only one which requires prerequisites. The prerequisites must be achieved before any points are awarded within that category. A commissioning process is required for mechanical, electrical, plumbing, renewable energy systems, and assemblies in accordance with ASHRAE Guide 0-2005 and ASHRAE Guideline 1.1-2007 (United States Green Building Council, 2018, p. 64). Commissioning is a process to make sure that the building is designed, constructed, operated, and maintained in accordance with owner's requirement (United States Green Building Council, 2018, p. 64). Projects must demonstrate an improvement in energy performance through: (1) performing a whole-building energy simulation to compare the proposed building with the baseline building, as described in ANSI/ASHRAE/IESNA 90.1-2010 standard; (2) ensuring compliance with the ASHRAE 50% Advanced Energy Design Guide; or (3) ensuring compliance with the ASHRAE Advanced Building Core Performance Guide (this option is only available for project of less than 100,000 ft^2) (United States Green Building Council, 2018, p. 66). Building-level energy consumption must be tracked and the data is used to support energy management (United States Green Building Council, 2018, p. 69). In addition, chlorofluorocarbon (CFC)-based refrigerants are forbidden in new heating, ventilating, air-conditioning, and refrigeration (HVAC&R) systems (United States Green Building Council, 2018, p. 70).

2.3.2.1.2 Energy Performance

In addition to meeting the prerequisites described above, to gain credits towards certificates, different energy performance standards and requirements need to be met. The project can gain credits if enhanced commissioning is done as follows: (1) enhanced system commissioning according to ASHRAE Guideline 0-2005 and ASHRAE Guideline 1.1-2007 for HVAC&R systems or enhanced and monitoring-based commissioning; or (2) envelope commissioning according to ASHRAE Guideline 0-2005 and National Institute of Building Sciences (NIBS) Guideline 3-2012 (United States Green Building Council, 2018, p. 71). The Optimize Energy Performance sub-category in LEED v4, accounts for 18 points out of 110 points for new construction (United States Green Building Council, 2018, p. 74). A project can gain credits if more than 6% improvement on energy performance for new construction, 4% for major renovation or 3% for core and shell is demonstrated through a whole-building energy simulation. To gain all 18 points for this category, a 50% improvement in new construction or a 48% improvement in a major renovation in energy performance is required. In addition, by complying with ASHRAE Advanced Energy Design Guide, a project can also gain points. However, a maximum of 6 points can be awarded by choosing this option (United States Green Building Council, 2018, p. 74). Another point will be credited if advanced energy metering is installed (United States Green Building Council, 2018, p. 77). Two additional points are possible by implementing demand response through load shedding or shifting (United States Green Building Council, 2018, p. 79).

2.3.2.1.3 Green Power

LEED v4 awards points for the use of renewable energy: one points will be credited if more than 1% energy is supplied by on-site renewable sources; full three credits are awarded if more than 10% energy is supplied by on-site renewable sources. Credits for enhanced refrigerant management can be achieved by either using no refrigerants (or low-impact refrigerants) or a calculation shows that refrigerant impact is blow required limits (United States Green Building Council, 2018, p. 82). LEED v4 encourages the use of green power and carbon offsets. To gain the credit in Green Power and Carbon Offsets, contracts with qualified resources need to specify that at least 50% of the project's energy is from green power, carbon offsets, or renewable energy certificates (RECs) (United States Green Building Council, 2015, p. 85).

2.3.2.2 ***Materials***

2.3.2.2.1 Prerequisites

LEED v4 addresses both extraction and use of materials. One of the prerequisites in this category is the requirement for storage and collection of recyclables (United States Green Building Council, 2018, p. 86). Dedicated storage areas for recyclable materials for the entire building are required. In addition, a construction and demolition waste management plan is required, in which, waste diversion goals and diversion strategies for at least five materials need to be elaborated (United States Green Building Council, 2018, p. 87).

2.3.2.2.2 Life Cycle Impact

Among all sub-categories in MR, Building Life Cycle Impact Reduction comprises the highest percentage of points. LEED v4 encourages the use of historic buildings or abandoned buildings; the projects will gain points in this sub-category if a historic building is reused or if an abandoned or blighted building is renovated. If materials are reused or salvaged from old buildings at 25% or more of the project surface area, points will be awarded in this sub-category (United States Green Building Council, 2018, p. 90). Another alternative in this category is to conduct a whole building LCA to demonstrate a 10% reduction in at least three environmental impacts out of six (United States Green Building Council, 2018, p. 90). The environmental impacts to be evaluated are global warming potential, depletion of the stratospheric ozone layer, acidification of land and water resources, eutrophication, the formation of tropospheric ozone, and depletion of nonrenewable energy resources. In this way, the newest version of LEED is working toward including LCA concepts into the rating system (United States Green Building Council, 2018, p. 92). In LEED v4, using a product with an environmental product declaration (EPD) conforming to a qualified program (e.g., ISO 14044) can add points in the MR category (United States Green Building Council, 2018, p. 93). If a product is certified by a third party on its efficacy to reduce environmental impacts (as listed in the previous paragraph), points can be gained as well. LEED v4 awards points for the use of products that have a publicly released report on the commitment to social and environmental responsibilities (United States Green Building Council, 2018, p. 95). In addition, the points can be gained through a demonstration of Leadership Extraction Practices (e.g., bio-based materials, materials reuse, and recycled content). LEED v4 also requires the use of materials with qualified material ingredient reporting or material ingredient optimization strategy through the GreenScreen v1.2 Benchmark or a Cradle-to-Cradle certificate. If a product demonstrates the optimization of manufacturer supply chain, one point can be gained as well (United States Green Building Council, 2018, p. 97).

2.3.2.2.3 Waste Management

Beyond the prerequisites for waste management, LEED v4 requires diverting at least 50% of the total construction and demolition material; the diverted materials must include as least three materials streams (United States Green Building Council, 2018, p. 106). An alternative to gain points in Waste Management is to control the construction waste content below 2.5 lb./ft^2 (United States Green Building Council, 2018, p. 106). In MR categories, LEED v4 also has requirements on heavy metal control, furniture, and design flexibility. However, most of the information is for healthcare, which is not applicable to this project. Therefore, the information on these sub-categories are not included nor discussed.

2.3.3 Green Globes

Green Globes is an assessment program to evaluate the environmental performance and sustainability of buildings of different types. Green Globes has three evaluation systems: New Construction, Existing Building, and Sustainable Interiors. Green Globes for New Construction (Green Globes NC) is developed for new construction, major renovation, and additions, which applies to the needs of this project. In Green Globes NC, points are distributed in seven different categories, and total 1000 points. Among them, Energy accounts for 390 points, which is nearly 40% of the total points, while Materials and Resources account for 125 points (Green Building Institute, 2015). Table 3 shows the levels and required points for certification in Green Globes NC. In Green Globes NC, the performance of the building is assessed based on the local climate. The climate information is obtained from ASHRAE/IES Standard 90.1-2013 (ASHRAE, 2013) as shown in Figure 2.2.

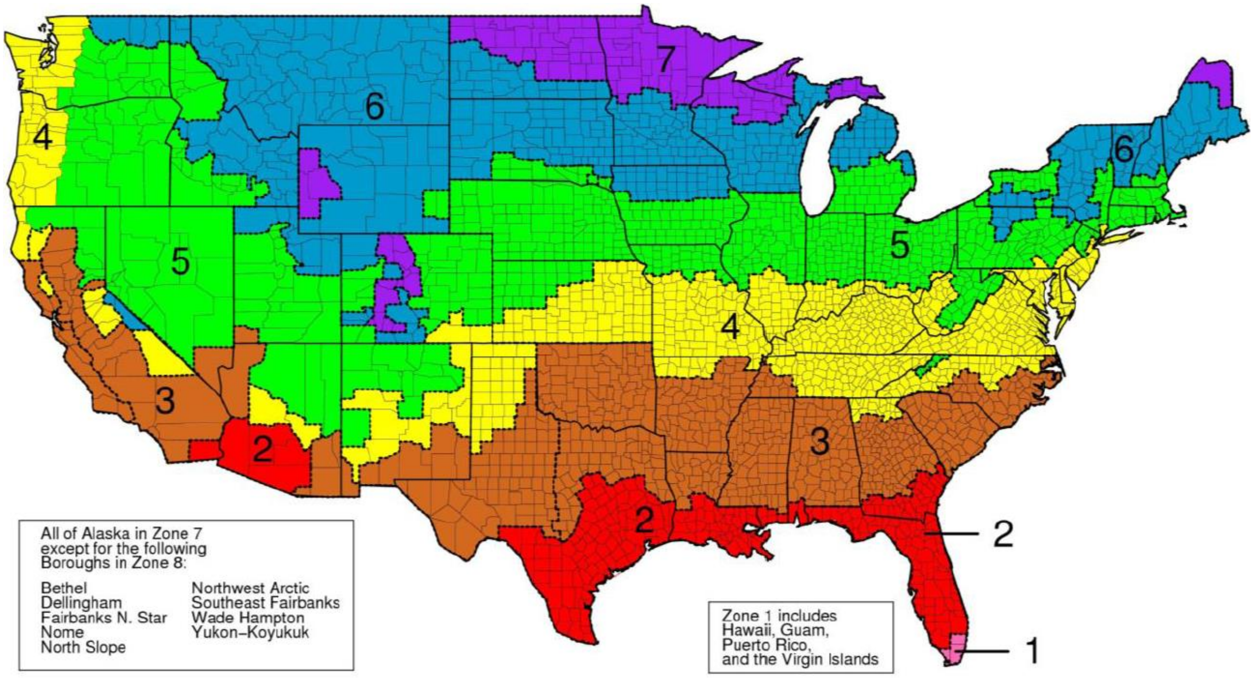


Figure 2.2. ASHRAE climate zone map (ASHRAE, 2013)

2.3.3.1 *Energy*

2.3.3.1.1 Energy Performance.

In Green Globes NC, one of the most important focuses is assessing energy performance, which has 100 points out of 390 points. There are four different paths to assess the energy performance of the building: (1) Energy Star® Target Finder; (2) ANSI/ASHRAE/IES Standard 90.1-2010, Appendix G; (3) ANSI/GBI 01-2010 Energy Performance Building Carbon Dioxide Equivalent Emissions (CO_2e); and (4) ASHRAE Building Energy Quotient (bEQ) rating system. Similar to LEED, the energy performance needs to be evaluated. Compared with LEED v4, Green Globes provides more options for energy performance evaluation. However, the whole building LCA is not included as an option as it is in LEED (Green Building Institute, n.d.).

Table 2.3. Percentage of Points Needed for Certification Levels in Green Globes for New Construction

Certification Levels	Percentage Required
One Green Globes	35-54%
Two Green Globes	55-69%
Three Green Globes	70-84%
Four Green Globes	85-100%

Green Globes NC encourages practitioners to estimate and anticipate energy use on an annual basis, and an energy conservation plan that includes reducing passive demand and power demand is desired (Green Globes, 2015, p. 75). For passive demand, there is a requirement for the minimum heat capacity of the building envelope gross wall, interior partitions, and return air plenums (5 Btu/ft^2). Passive demand also requires a thermal energy storage system to offset the peak cooling demand more than 30%. For power demand, the rating system requires an increase in monthly power demand factor (low volatility in power usage) and a reduction in total power demand (Green Globes, 2015, p. 76).

Green Globes NC encourages building-level metering of electricity, heating fuels, and steam. In addition, sub-metering awards points on lighting, plug loads, major electric HVAC equipment, chilled water generation, on-site renewable energy power generation, heating water or steam generation, specialty or process electrical equipment, and critical HVAC controls (Green Globes, 2015, p. 82). Green Globes NC specifies the R-value and U-/C-/F-factor for different construction components based on the climate zone where the project locates (refer to Table 3.3.4.1.1-A and Table 3.3.4.1.1-B in the Green Globes NC) (Green Globes, 2015, p. 88). The orientation of the building is taken into consideration in Green Globes NC as well; points are awarded if the ratio of the north/south fenestration area to the east/west fenestration area is between 1.25 and 2.00. In addition, the U-factor of the fenestration needs to be less or equal than a specified value (as seen in Table 3.3.4.3 in the Green Globes NC) (Green Globes, 2015, p. 90).

The lighting condition for a building is evaluated by total lighting power density (LPD). LPD is the load of lighting in a defined area (ASHRAE, 2013). In Green Globes NC, LPD needs to meet the required value through either the building-area-method or space-by-space method (description of the methods can be found in ANSI/ASHRAE/IES Standard 90.1-2010). Interior automatic light shutoff controls, light reduction controls, and daylighting are encouraged (Green Globes, 2015, p. 91). For exterior lighting system, lamps with an initial efficacy of at least 60 lumens per watt, LED lamp sources, lamp sources with no mercury content, and lighting systems with photo sensors or an astronomical time switch are encouraged (Green Globes, 2015, p. 97).

2.3.3.1.2 HVAC Requirement

A central building automation system (BAS) is desired for HVAC systems. ANSI/ASHRAE/IES Standard 90.1-2010 needs to be referenced for the cooling equipment base efficiency (Green Globes, 2015, p. 102). In cooling towers, the use of two-speed fans or variable-speed fans to reduce energy consumption is encouraged (Green Globes, 2015, p. 106). It is suggested that a waterside economizer system uses outdoor air for cooling water. Heat pump efficiency is evaluated with a heating seasonal performance factor (HSPF) and coefficient of performance (COP) based on ANSI/ASHRAE/IES Standard 90.1-2010 or International Energy Conservation Code (IECC) 2009. In addition, heating equipment performance needs to be evaluated on its annual fuel efficiency, thermal efficiency, and combustion efficiency according to ANSI/ASHRAE/IES Standard 90.1-2010 or International Energy Conservation Code (IECC) 2009 (Green Globes, 2015, p. 107). If a steam heating system is equipped to recover and return condensate, points are awarded for a condensate return over 50% (Green Globes, 2015, p. 107). The steam trap designs need to be stamped by a professional engineer and have isolation valves for repairs. Water heaters should be equipped with intermittent electrical igniters and low NO_x burners, and the heaters should meet the efficiency requirement in ANSI/ASHRAE/IES Standard 90.1-2010 or International Energy Conservation Code (IECC) 2009 (Green Globes, 2015, p. 109).

The HVAC design should minimize or eliminate reheating and recooling (Green Globes, 2015, p. 110). Controls to shut down the outdoor air and exhaust air dampers when the system is not operating are desired (Green Globes, 2015, p. 111). A leakage rate of less than 5% for the air handling system is required (Green Globes, 2015, p. 111). The duct systems should also meet the requirements on noise level (Green Globes, 2015, p. 112). The use of flexible ductwork should consider the limitations on length, position, and support (Green Globes, 2015, p. 113). The duct joints should be sealed, and the leak rate should not exceed 5%. For the fans used in HVAC systems, the motors should meet NEMA's Premium Energy Efficiency Motor Program, and the speed of the variable speed fans should be controlled by a duct pressure set-point or an energy management control system (Green Globes, 2015, p. 114).

2.3.3.1.3 Operations

For ventilation, occupancy and CO_2 sensors should be installed to monitor the occupancy rate and thus control the ventilation rates (Green Globes, 2015, p. 115). The sensors should be calibrated every year to keep the error within 2%. Pressure-drop impact on fan power, bypass for economizer operation and MERV 13 filtration should be considered for the ventilation heat recovery system. Variable refrigerant flow system technology should be utilized in the HVAC design (Green Globes, 2015, p. 115). Energy efficient lighting fixtures, lamps, ballasts, motors, and other equipment are preferred in the Green Globes NC program (Green Globes, 2015, p. 117).

2.3.3.1.4 Renewable Energy

On-site renewable energy technology, such as wind, biomass, geothermal, photovoltaics, and solar, are encouraged to be used (Green Globes, 2015, p. 118). On-site renewable energy feasibility studies are preferred, and the recommendations from feasibility studies should be implemented. Additionally, points can be awarded if off-site renewable energy, such as certified green power or renewable energy certificates (RECs) are used for at least 10% of the electrical consumption for a minimum of three years (Green Globes, 2015, p. 119).

2.3.3.2 *Materials and Resources*

2.3.3.2.1 Product Declaration

Green Globes NC suggests assessing building core and shell based on the materials used for the building. There are two typical paths described in Green Globes NC, one is the performance path, which uses LCA to assess the environmental impact of the core and shell; and the other is the prescriptive path, which identifies materials and products that have EPDs, third-party certifications, third-party LCA or third-party sustainable forestry certifications (Green Globes, 2015, p. 142). For the prescriptive path, at least 10% of materials and products need to be qualified for certification requirement as mentioned above to gain points. For interior fit-outs assessment, Green Globes NC also suggests two paths: one is the performance path based on LCA, and the other is the prescriptive path based on the EPDs and third-party certifications (Green Globes, 2015, p. 147).

2.3.3.2.2 Materials Reuse and Waste Management

Similar to LEED v4, Green Globes NC encourages the reuse of existing structures (Green Globes, 2015, p. 151). At least 10% reuse of facades, 10% reuse of current structures, or 10% reuse of non-structural elements or existing furnishings can contribute to awarding of points. More points can be awarded if a higher percentage reuse rate is achieved in each one of the categories mentioned above (Green Globes, 2015, p. 152).

As far as waste control, Green Globes NC awards points if more than 25% construction wastes are diverted. Reuse of existing on-site materials is also encouraged (Green Globes, 2015, p. 154). For operational waste, an operational flow for waste handling and storage is needed. Storage areas for recyclable waste should be set at both pick-up areas and points of service. In addition, operational flow for handling and storage facilities for composting is required (Green Globes, 2015, p. 155).

Green Globes NC suggests a preliminary Building Service Life Plan that includes the expected service life of the building (Green Globes, 2015, p. 156). In addition, a plan of replacement of structural systems, building envelope, and hardscape materials is suggested. During the service life, the mechanical, electrical, plumbing and energy generation systems need to be inspected for replacement (Green Globes, 2015, p. 157). Green Globes NC encourages the design of projects that specify the use of prefabricated, preassembled, and modular products and minimize the use of raw materials (Green Globes, 2015, p. 158). The design should use raw materials efficiently, when compared with typical construction practice, and examples of efficient use of raw materials should be given. The design should incorporate assemblies which perform multiple functions. The design should consider the future deconstruction, demounting, and disassembly (Green Globes, 2015, p. 160).

2.3.3.2.3 Building Envelope

Green Globes NC has very specific requirements on design, field testing, and installation for building envelopes (Green Globes, 2015, p. 161). The roof membrane assemblies, flashing, metal sheet, cladding, and other materials for building envelopes should be installed according to the manufacturer's instructions or recommendations, and the installation should be inspected by manufacturer technical personnel or a certified third-party inspector (Green Globes, 2015, pp. 162–176). A moisture management design on roof and wall openings should be established according to industry requirements, such as AAMA/WDMA/CSA 101/I.S.2/A440-8, or industry best practice (Green Globes, 2015). The air barrier material and vapor retarders (if used) should be documented in the construction documents. The compliance of the continuous air barrier for the opaque building envelope should be tested by one of the following standards: ASTM E 2178-11, ASTM E 2357-11 and ASTM E 779-03 (ASTM International, 2010, ASTM International, 2011b, ASTM International, 2013; Green Globes, 2015).

2.3.4 Living Building Challenge Version 3.0

Similar to LEED and Green Globes, the Living Building Challenge (LBC) is a certification program which initiates advanced measures to assess the sustainability of the built environment. LBC focuses on seven performance categories (petals): places, water, energy, health and happiness, materials, equity, and beauty. Each sub-category under the petals is imperative. A project can be certified in three paths: Living Building Certification, Petal Certification, and Zero Energy Building Certification (International Living Future Institute, 2016). Besides evaluating the sustainability of the building, LBC also focuses on the interaction between the human and built environment, as well as the social impacts of the building. However, due to the defined scope of this project, only the specifics in the energy and materials petals of LBC are discussed.

2.3.4.1 ***Net Positive Energy***

According to the Energy Petal Handbook (International Living Future Institute, n.d.), 105% of project energy must be produced by renewable energy (no combustion-based) annually. To meet the requirement, the energy must be provided on-site, and on-site energy storage facilities must be used. It also requires the process of energy production in a safe and pollution-free manner. Net Positive Energy requires an energy storage facility in case of the need of emergency lighting for up to one week. All energy-consuming equipment and systems need to be included in the energy budget. Purchasing off-set REC is not an option for this challenge (International Living Future Institute, n.d.). All major energy uses must be sub-metered. If the whole building system cannot be sub-metered, the HVAC system (heating, cooling, and fans) should be sub-metered for its energy. The building performance period is considered for a consecutive 12-month timeline after full occupancy. Requirements of the Net Positive Energy challenge must be met during the performance period (International Living Future Institute, n.d.).

2.3.4.2 *Materials*

In the Materials petal, LBC encourages using materials that are non-toxic, ecologically regenerative, transparent, and socially equitable.

2.3.4.2.1 Red List

The LBC Materials Petal Handbook (International Living Future Institute, n.d.) listed 22 harmful/toxic chemicals, which are categorized as red list materials (seen in Table 2.4). These chemicals are not allowed in the project, except for products that contain these chemicals naturally. The Chemical Abstract Service (CAS) number is required for every known chemical. All wet-applied products must meet the requirements of volatile organic compounds (VOCs) emissions standards. The VOC level must be below the South Coast Air Quality Management District (SCAQMD) Rule 1168 for Adhesive and Sealants or the California Air Resources Board (CARB) 2007 for Architecture Coatings. Declaration is required for building materials. Information from the Cradle-to-Cradle Certified Product Standard (C2C), Health Product Declaration (HPD), and Pharos database can be used (International Living Future Institute, n.d.).

Table 2.4. Chemicals in the Living Building Challenge Red List (International Living Future Institute, n.d.)

Alkylphenols	Halogenated Flame Retardants (HFRs)
Asbestos	Lead (added)
Bisphenol A (BPA)	Mercury
Cadmium	Perfluorinated Compounds (PFCs)
Chlorinated Polyethylene and Chlorosulfonated Polyethylene	Polychlorinated Biphenyls (PCBs)
Chlorobenzenes	Phthalates
Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs)	Polyvinyl Chloride (PVC)
Chloroprene (Neoprene)	Polyvinylidene Chloride (PVDC)
Chromium VI	Short Chain Chlorinated Paraffins
Chlorinated Polyvinyl Chloride (CPVC)	Wood treatments containing Creosote, Arsenic or Pentachlorophenol
Formaldehyde (added)	Volatile Organic Compounds (VOCs) in wet applied products

2.3.4.2.2 Embodied Carbon Footprint

In LBC 3.0 (International Living Future Institute, 2016), embodied carbon needs to be reduced by using different strategies. Total embodied carbon (tCO_2e) must include the carbon generated from construction materials and processes (International Living Future Institute, n.d.). One of the commonly used strategies is purchasing Certified Emission Reductions (CERs) or Verified Emission

Reductions (VERs) through an approved program to offset the total construction-based carbon contribution (International Living Future Institute, n.d.).

2.3.4.2.3 Responsible Industry

This imperative aims at limiting environmental and social impacts caused by natural resource extraction and plant cultivation. All materials used must be certified by third-party certified standards and fair labor practices. In addition, one Declare product is required for every 500 square meters of gross building area. Declare is an online building materials database, which discloses the ingredients of materials (International Living Future Institute, 2014b, p. 26).

2.3.4.2.4 Living Economy Sourcing

To support the local economy, LBC encourages the use of locally manufactured materials. The restrictions applied are shown in Table 2..

Table 2.5. Restriction in the Living Building Source Imperative (International Living Future Institute, n.d.)

Materials construction budget	Distance from construction site
20% or more	Within 310 miles (500 km)
Additional 30% or more	Within 620 miles (1000 km)
Additional 25% or more	Within 3,100 miles (5,000 km)
Additional 20%	No restriction

In addition, consultants hired for the project must come from within 1,550 miles from the construction site.

2.3.4.2.5 Net Positive Waste

A Waste Conservation Management Plan must be incorporated from the design phase to the construction phase, and then from the operation phase until the end of life phase. Construction teams are encouraged to develop innovative approaches to reduce the amount of waste produced. For every 5380 ft^2 (500 m^2) of gross building area, at least one product made of salvaged materials must be used. More than 90% of materials must be diverted from landfills; detailed requirements can be found in the Materials Petal Handbook (International Living Future Institute, n.d.). Hazardous materials are not included in this requirement. All hazardous materials need to be documented and dealt with properly (International Living Future Institute, n.d.).

2.3.5 Comparison of three rating systems

In Green Globes NC and LEED v4, projects are certified by accumulating points in each of several categories, which vary between the standards. Certification is awarded based on the total points earned by the project. Each category is broken down into different sub-categories. Therefore, these rating systems are easy to follow, and project teams can take advantage of this to optimize the funding and resources to maximize the total points. In these two rating systems, the categorization methods and focuses of interest are different. Green Globes NC provides more details and specifics than LEED v4. However, LEED v4 is more recognized both nationwide and worldwide. On the other hand, under LBC 3.0, certification is not awarded through accumulation of points, but rather based on if the project accomplishes the required challenge. In most cases, it is not specified how the project team should achieve the requirement. Compared to the other rating systems, LBC leaves project teams more flexibility in achieving sustainable construction. Based on the reviews of the three rating systems, similarities and differences are shown in Table 6 and Table 7.

Table 2.6. Comparison of LEED v4 BD+C, Green Globes NC, and Living Building Challenge 3.0 (Energy)

		LEED V4 BD+C	Green Globes NC	LBC 3.0
Prerequisites		**Yes**	**No**	**No**
Commissioning		Yes. Enhanced system commissioning, enhanced monitoring-based commissioning, and envelope commissioning are required.	Yes, but the points are counted in Project Management instead of Energy category.	Not specifically mentioned. No specific document required.
Building Energy Performance		1. Building energy simulation is used to calculate improvement of energy performance; 2. ASHRAE Design Guide.	1. Energy Star Target Finder; 2. ASHRAE 90.1-2010 Appendix G; 3. ANSI/GBA 01-2010; 4. ASHRAE bEQ.	No specific requirement on energy performance.
Metering	Whole building metering	Yes	Yes	Yes
	Sub-metering	For individual energy end uses that represent 10% or more of the total annual consumption of the building.	Lighting, plug loads, major HVAC equipment, chilled water generation, on-site renewable energy generation, heating water and steam generation, specialty or process electrical equipment.	HVAC system needs to be metered if the whole unit cannot be metered.
Demand Response		Yes. Participation in demand response program is specified.	Not specified. The requirements of passive demand reduction and power demand reduction are specified.	Not specified.

Renewable Sources of Energy	Renewable energy	Yes. Also have requirement on production.	Yes	Yes. However, no combustion is allowed. Net positive energy is required.
	RECs or carbon offsets	At least 50%.	Yes	In Materials petal, embodied carbon needs to be offset.
Building Envelope	Opaque envelope	Included in enhanced commissioning and energy performance simulation.	R-values, U-, C-, F- factors.	Not specifically mentioned.
	Orientation	Mostly included in Integrative Process.	Yes. Orientation factor.	No requirement.
Lighting	Lighting power density	Included in Indoor Environmental Quality.	Included for points award.	No requirement.
	Auto shutoff controls	Included in Indoor Environmental Quality.	Included for points award.	No requirement.
HVAC Systems	Building automation system	Not specified for points award.	Included for points award.	Not specifically mentioned.
	Other HVAC systems and control	Included in whole building simulation.	Detailed specifications for major HVAC equipment.	No specific requirement.
Refrigerant Management		No refrigerants or low-impact refrigerants.	Included in Emission and Other Impacts.	Yes. Specified in Red List.
Energy Efficient Transportation		Included in Sustainable Site.	Yes. Specifications on location selection.	Yes. Specified in Human Power Living.

Table 2.7. Comparison of LEED v4 BD+C, Green Globes NC, and Living Challenge 3.0 (Materials)

		LEED V4 BD+C	Green Globes NC	Living Challenge 3.0
Prerequisites		**Yes**	**No**	**No**
Life-cycle impact	Historic building reuse	Yes.	Yes. Structural element.	Strongly encouraged.
	Renovation of abandoned or blighted building	Yes	Not specifically mentioned.	Strongly encouraged.
	Building material reuse	Yes	Yes. Non-structural element. Also in waste management plan.	At least one salvaged material must be used for every 5380 ft^2 gross area.
	Whole building life cycle impact	Yes. But only a small portion.	Yes. Performance path for building core and shell & interior outfits. Relatively important.	C2C product standard can be used for materials certification.
Building Product Disclosure and Optimization	EPD	At least 20 different permanently installed products from five different manufacturers.	Yes. Prescriptive path for building core and shell, and interior outfits.	EPD is not specifically mentioned.
	HPD	Not specifically mentioned.	Not specifically mentioned.	Yes. HPD can be used to exclude materials that contain chemicals in Red List.
	Declare product	Not required.	Not required.	Required in Responsible Industry. At least one Declare product must be used for every 5380 ft^2 of gross project area.

	Multi-attribute optimization	Third-party certified products showed reduction in multiple environmental impacts or USGBC approved program.	Yes. Prescriptive path for building core and shell and interior outfits.	At least one salvaged material must be used for every 5380 ft^2 of gross area.
	Report source of the materials	Yes. Extraction report or leadership extraction practices.	Yes. Resource conservation. Specify the source of raw materials.	Yes. Specified in Responsible Industry.
	Materials ingredients	Ingredients reporting or ingredient optimization or supply chain optimization.	Not specifically mentioned.	Yes. Mostly used to exclude materials containing chemicals in Red List.
Waste Management		Diversion or reduction of total waste material.	At least 25% diversion.	Yes. A Material Conservation Management Plan should be developed to minimize the waste. Over 90% construction waste should be diverted.
Building Service Life	Building service life plan	Mentioned in whole-building life cycle assessment.	Yes. Detailed plan on service life, maintenance and repair is needed.	Not specifically mentioned.
Resource Conservation	Multi-functional assemblies	Not mentioned in LEED.	Yes	Not mentioned in LBC.
Building envelope		Mostly included in Indoor Environmental Quality.	Yes. Specifics on roofing, flashings, cladding, wall openings, barriers and foundation.	No specific requirement.

In summary, these three rating systems have different focuses. However, it is clear that all three rating systems have an agreement on using renewable energy and products with LCA certification or EPD certification. A best practice guide for a sustainable maintenance facility should be provided with a combination of the recommendations from these three systems. Therefore, a single rating system should not be strictly adhered to, since each of them has its benefits and limitations. In this way, the best practice guide can provide flexibility for ODOT on the design and building of sustainable maintenance facilities.

2.4 DOT REGULATIONS

2.4.1 Related DOT policies

With the improving recognition of green building and sustainable construction, DOTs from different states across the U.S. are trying to implement policies, regulations, and codes to promote the use of renewable energy, environmentally friendly materials, water efficiency techniques, and other new construction techniques.

In Oregon, the concept of sustainability is defined in Oregon Revised Statues (ORS) 184.421 (ORS, 2013a), while sustainability goals are described in ORS 184.423 (ORS, 2013b). One of these goals is to improve the efficiency of the use of energy, water, and resources; another is to invest in facilities, equipment and goods with highest feasible efficacy and lowest life cycle cost (ORS, 2013b). To pursue these goals, different codes, standards, and policies were developed. The Building Code Division has implemented policies, standards, and regulations on energy efficiency, use of renewable energy, and water conservation (Oregon Building Codes Division, 2008).

The Oregon Smart Guide was published to provide guidelines on water conservation and rainwater harvesting. In addition, Statewide Alternate Methods (SAM) to the building code were published to support green building and sustainable construction technology and practices. SAM provides information on water conservation, rainwater harvesting, and solar water heating systems for both residential and commercial buildings. Senate Bill (SB) 79 was approved in 2009, which directs the task force of Building Code Division to reduce energy use in both residential and commercial construction (75th Oregon Legislative Assembly, 2009). House Bill (HB) 2950, which approved in 2009, created a Construction Industry Energy Board as an advisory board to streamline the adoption of innovative energy practices and products (The Oregonian, n.d.).

In 2014, the Oregon Energy Efficiency Specialty Code (OEESC) reduced the energy use in newly-built commercial buildings by more than 15% compared to 2007 code (Building Codes Division, n.d.). Oregon Reach Code (ORC) is an optional standard in supplemental to standard building code to reduce energy use. In 2010, the Oregon Solar Installation Specialty Code (OSISC) provided guidelines for installation of PV systems. The State Energy Efficient Design (SEED) program was developed to promote the design, construction, and renovation of highly efficient buildings owned or operated by Oregon agencies (Lorand, Cohen, Mello, & Panich, 2013). Oregon Department of Administrative Services (DAS) approved the DAS 125-6-010, which required state-owned buildings to be designed to meet LEED v2 Silver status (Department of Administrative Services, 2004). In addition, the ODOT Sustainability Plan requires major facilities to follow SEED rules and LEED guidelines; additionally, cost-effective technology needs to be investigated and incorporated into existed and new facilities (Oregon Department of Transportation, 2012).

In the state of Washington, the State Solid and Hazardous Waste Plan was implemented to provide guidelines for reducing hazardous wastes (in the form of solid, semi-solid, liquid and contained gases) and toxics. In addition, the state of Washington passed the law 39.35D RCW High-Performance Public Buildings law, in which state projects that receive capital budgets must achieve LEED silver status (Hammond, 2008; Turner & Henderson, 2010). California's Green Building Code has been mandatory for all buildings in California since 2010 (CBSC & ICC, 2013). Therefore, the experiences from the states close to Oregon can be examined and used for developing practices for constructing sustainable, cost-effective maintenance facilities.

2.4.2 SEED Rules

ODOT agencies are required to adhere to ORS 276.900-915. ORS 276.900-915 established the State Energy Efficient Design program, which requires energy use in newly constructed or significantly remodeled state agency buildings to be minimized through the incorporation of the Optimum Energy Conservation Measures, and that buildings be designed to use 20% less energy than an equivalent code level building. In SEED rules (OAR 330-130), there are two building classes: Class 1 buildings and Class 2 buildings. Class 1 buildings are new buildings, additions, or renovations of 10,000 ft^2 or more of heated or cooled floor area or building additions that increase the existing building to 10,000 ft^2 or more. Class 2 buildings are new buildings or renovations that occupy less than 10,000 ft^2 (Nathwani, J., & National Renewable Energy Laboratory (U.S.), 2004).

The SEED program has specific requirements at each phase, from the initial project meeting to the occupancy phase. The procedures for Class 1 and Class 2 buildings are different. Class 1 projects require that the agency work with an energy analyst to select energy conservation measures and document through a building simulation model that the proposed building will perform 20% better than an equivalent code level building. The goal of "20% better than the state energy code" should be included in the contract and discussed in initial meetings (Oregon Department of Energy, 2004). ODOT must coordinate an Initial meeting with ODOE early in the programming phase of the project. During this Initial Meeting, the scope of the project will be discussed and preliminary discussions regarding the project design, integrated energy design approach, the modeling approach, and the systems performance verification plan will take place. At the Scoping Meeting, the energy conservation measures (ECMs) are selected for baseline incorporation or analysis. During the design development phase of the project, modeling of the ECMs takes place to determine energy savings of the selected measures, measure cost estimates are obtained and cost-effectiveness of individual ECMs are determined. With this information, an ECM package is selected that ensures that the proposed design will perform at least 20% better than a code equivalent building. The Preliminary SEED Energy Analysis report is then sent to ODOE for review. After review of the report, an ECM review meeting is held to discuss selected ECMs, the performance verification plan and the metering plan. During the construction documents phase, it is incumbent on ODOT to verify that the selected ECMs are included in the drawings and specifications. The Energy Systems Verification Plan is developed, along with the Metering plan. Construction documents must be submitted to the Oregon

Department of Energy, no later than at 90% design completion to allow for ODOE review and feedback before the project is bid. The energy systems performance verification plan, metering plan and final SEED energy analysis report need to be submitted in this phase. In the construction phase, the commissioning agent needs to verify that all ECMs are installed properly and operating efficiently. Upon occupancy of the building, the energy use needs to be monitored for at least 18 months and reported to ODOE. If significant differences between the actual energy use and the model predictions result, the agency must investigate to find the cause, so that an adjustment can be made to the operation of the building; or an explanation for the difference can be found that is acceptable to the agency and the department. (Oregon Department of Energy, 2017). The building will be given the SEED Award if it complies with the SEED rules and meets the standard of a "highly energy efficient building."

2.4.3 Regulations and case studies from other DOTs

The maintenance facility at Sisters is the first facility in Oregon using renewable energy (geothermal and solar water heating). Additionally, other states have constructed facilities using renewable energy, advanced waste management, and new construction techniques to achieve sustainability goals. These experiences can be valuable to ODOT for developing best practices for sustainable maintenance facility construction. In this section, regulations and case studies from different state DOTs are discussed.

2.4.3.1 *California*

California enforced a green building code, which requires the California Building Energy Efficiency Standards to be met or exceeded. California is currently the only state which enforces a green building code on both residential and non-residential construction. Conducting a whole-building LCA can contribute to the award of CALGreen Tier 1 and CALGreen Tier 2 (CBSC & ICC, 2013). Due to sufficient sunshine, many maintenance stations install PV modules to produce electricity. In 2006, Caltrans was approved for installation of PV panels at 70 facilities through Clean Renewable Energy Bonds (CREB) (United States Department of Energy, n.d.-b). Figure 2.3 shows the PV system installed at the Sunrise Maintenance Facility through the CREB program. This system generated 46,546 kWh electricity from June 2010 to May 2011, which saved $6,703 in utility bills (Lorand et al., 2013). The estimated payback period is 23 years with a $40,000 incentive from the Sacramento Municipal Utility District (Lorand et al., 2013).

Figure 2.3. PV system at sunrise maintenance station in California (Lorand et al., 2013)

2.4.3.2 *Colorado*

A 102-kW PV solar energy array was installed at the City of Denver Public Works Department Central Platte Campus in Denver, CO (Figure 2.4). The fleet maintenance building and warehouse building each achieved LEED Gold certification. The system can generate 153,500 kWh annually, which is estimated to save $200,000 if the system serves more than 20 years (Lorand et al., 2013).

2.4.3.3 *Hawaii*

A corrosion resistant roof with integrated PV system was installed at the Kilauea Military Camp in Hawaii. The PV system consists of 200 thin-film panels laminated on an aluminum-zinc coated standing seam metal roof and coated with an anticorrosion coating. This system generated 19,128 kWh electricity over the first-year operation, which saved $6,792 in energy costs in utility bill. The payback period for the system is estimated to be 29 years (Lorand et al., 2013).

Figure 2.4. PV solar energy array installed at the City of Denver Public Works Department Central Platte Campus in Colorado (Lorand et al., 2013).

2.4.3.4 *Indiana*

A public transportation maintenance facility in South Bend, IN adopted multiple sustainable energy strategies to achieve LEED platinum certification. A 93.5-kW thin-film PV solar energy system was installed (Figure 2.5). This system was estimated to generate 97,259 kWh electricity annually, which would meet 7% of the total electricity need. A geothermal system was installed to provide space conditioning for office area. Day lighting and automatic lighting fixtures were also applied. The building envelope and systems improvements were expected to save 39.8% energy costs and 54.1% energy consumption annually, when comparing to the ASHRAE 90.1-2004 baseline building (minimum performance value). In addition, RECs equivalent to 35% of the total electricity were purchased. This building was designed to eliminate CO_2 emissions by 2030 (the 2030 Challenge) (Architecture 2030, 2002; Lorand et al., 2013).

Figure 2.5. Thin-film PV system on a maintenance station roof in South Bend, IN (Lorand et al., 2013).

2.4.3.5 *Maine*

An Environmental Management System (EMS) was established for all MDOT facilities. Policy of Health and Safety Administration (OSHA), local environmental regulations and procedure manuals were incorporated into the EMS (Marie, 2004).

2.4.3.6 *Massachusetts*

The highway division of MassDOT developed an EMS to provide guidelines on activities at maintenance facilities. The EMS, which focused on hazardous waste and hazardous materials, were implemented (Marie, 2004). In this EMS, generation of hazardous waste is limited. All hazardous waste and materials are stored and treated in designated area at all maintenance facilities.

2.4.3.7 ***Minnesota***

At the Elm Creek Park facility in Minnesota owned by MN-DOT, heat is supplied by a geothermal well field. Two water-to-air heat pumps are used for supplying hot and cold air to the offices, and the conditioned air is distributed by a fan unit. Annual savings of $2,000 on heating and cooling are expected by using the geothermal system (Lorand et al., 2013).

2.4.3.8 ***Missouri***

The maintenance facility in St. Clair, MO operated by MoDOT (Lorand et al., 2013) has an installed roof-mounted solar air heating system as a supplemental heat supply (Figure 2.6). This solar air system consists of 40 collectors which are used to warm the air collected from the building. There are also two solar water heating systems; each of is equipped with four solar liquid collectors. During the summer time, the solar heating water system can supply most of the energy for water heating. The total cost for solar air heating and solar water heating systems are $154,000. The estimated payback period for solar air heating system is 91.7 years and 13.7 years for solar water heating system. In addition, two 1.2-kW wind turbines were installed at the Conway Welcome Center and a 16.5-kW solar panel system was installed at the MoDOT District Office in Joplin, MO.

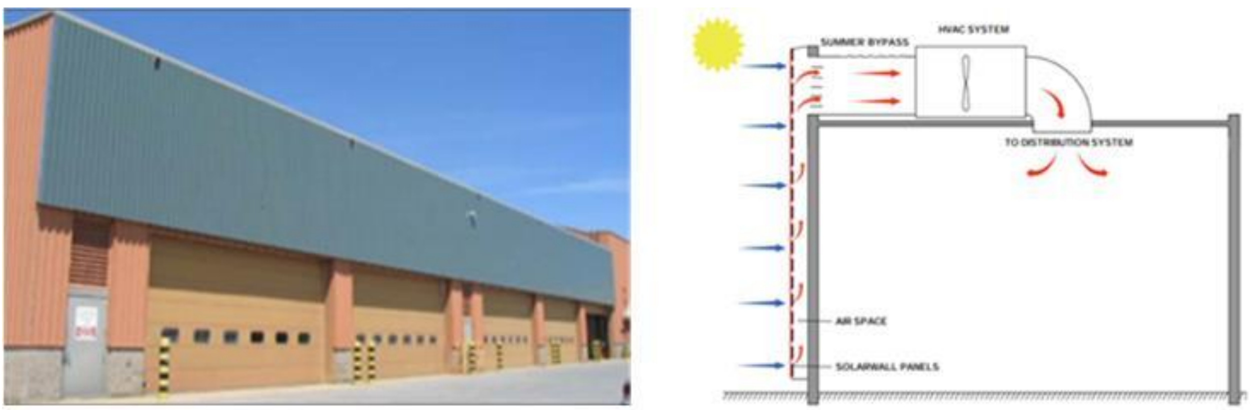
Figure 2.6. Solar air heating system installed on the roof of the maintenance facility in St. Clair, MO (J. E. Foster, 2015).

2.4.3.9 ***New Hampshire***

NHDOT developed an Inventory of Managed Properties (IMP) to manage the hazardous materials at their maintenance and operation facilities (Marie, 2004). This protocol focuses on early detection of potential environmental risks. IMP is currently only used for hazardous material and waste management. With the development of database, the system will also be used to document storm water management.

2.4.3.10 *New York*

Solar ventilation air heating systems with more than 110,000 ft^2 of solar collectors were installed at the U.S. Army's Fort Drum maintenance stations (Lorand et al., 2013). The systems employ a perforated corrugated metal cladding as the solar collector (Figure 2.7 (A)). The collectors are attached to the wall on the south face of the building, and a space between the collectors and walls is left for airflow collection (Figure 2.7 (B)). The estimated annual output of the system is 31,022 MMBtu. The system is estimated to reduce greenhouse gas emissions by 2,000 tons carbon dioxide equivalent (CO_2e) annually. Total cost of the system was $3.4 million, and an 8.5-year payback period was expected. A similar solar ventilation air heating system was used in four buildings at the Plattsburgh International Airport. The annual output of the 3,500 ft^2 of collectors was 365 MMBtu, which saved 521 MMBtu natural gas, and reduced about 21 tons of CO_2e.



(A) (B)

Figure 2.7. Solar air system at the Fort Drum vehicle maintenance facility: (A) unglazed transpired collectors; (B) illustration of the air heating system (Lorand et al., 2013).

In addition, a solar water heating system was installed at a train maintenance facility in Coney Island, NY. Evacuated-tube solar collectors were used to provide heated water; the evacuated-tube solar collectors operated more efficiently in cold weather than flat plate solar collectors. The system reduces the hot water electricity load by 67%.

2.4.3.11 *Ohio*

A 32-kW horizontal-axis wind turbine was installed at the Ohio Northwood Outpost (Lorand et al., 2013). This system offsets 65% of the electrical usage on an annual basis. Figure 2.8 shows the wind turbine in Ohio.

Figure 2.8. The 32-kW wind turbine at the Ohio Northwood outpost (Lorand et al., 2013).

2.4.3.12 *Pennsylvania*

PennDOT District 10 developed a Strategic Environmental Management Program (SEMP), which implemented procedures to improve environmental performance (Marie, 2004).

2.4.3.13 *Utah*

The U.S. DOE and Utah DOT provided funding to install a 1.8-kW-rated turbine at the Milford Maintenance Station, Utah. The estimated saving is 3,000 kWh annually (Lorand et al., 2013). The payback period for this turbine is 16 years.

2.4.3.14 *Washington*

Washington passed RCW 39.35D.030 "High Performance Green Building" in 2005. According to RCW 39.35D.030, all major facility projects of public agencies in the state of Washington which receive funding in a state capital budget or through a financing contract (as described in RCW 39.94.020) need to be certified to at least a LEED silver standard (Hammond, 2008; Turner & Henderson, 2010).

The maintenance building at the Monroe Correctional Complex in Monroe, WA is a LEED silver certified project. This maintenance building was built on the site of a dilapidated barn. An old wall of ecology blocks was preserved and used as a retaining wall for the new building. Rocks and concrete from the old barn were collected and crushed to be used as the road base for the new parking lot. Natural lighting is enhanced by additional windows in the rolling door and a skylight. Heating in this building is provided by propane. RECs were purchased to offset 50% of the baseline electrical load (Washington Department of Corrections, 2016).

2.5 SUMMARY

Life Cycle Analysis (LCA) and Life Cycle Cost Analysis (LCCA) can be used simultaneously to capture the environmental and cost contribution of buildings and building systems effectively. Both methods are designed to deal with complex systems with significantly large input data. Uncertainties and variability are challenges that users of either method must address adequately. LCA is a systemic phased approach, which consists of four components: goal definition and scoping, inventory analysis, impact assessment, and interpretation. By performing LCA, analysts and decision makers can (United States Environmental Protection Agency, 2006b):

- Develop a systemic evaluation of environmental output from a given a product
- Analyze the environmental trade-offs
- Quantify environmental releases through commonly known pathways
- Assist in identifying significant shifts in environmental impacts between life cycle stages spatial boundaries
- Assess human and ecological impacts
- Compare the health and ecological impacts
- Identify impacts to specific environmental concerns

LCCA is an economic analysis tool that goes beyond considerations for short-term investment goals or low investment costs. LCCA is most effective at assisting decision-makers to choose the most cost-effective design alternative based on specific investment goals. The cost considerations of LCCA include investment related costs, operational costs, single payment costs, recurring costs, present costs, and future costs. LCCA analysts can utilize the existing tables of PV factors, as well as sophisticated computer software to simplify computational requirements.

Three of the most commonly used green building rating systems in North America were reviewed. Among all three reviewed rating systems, LEED v4 and Green Globes NC are easier to follow and adopt, since a point-based rating system is used to provide guidelines. The Living Building Challenge is more flexible; project teams have more choices to decide the approach to complete the challenge. However, meeting net zero energy and net zero water are significant challenges in this approach. Despite the different focuses and approaches, there are still similarities among them: using renewable energy in construction projects is preferred in all three rating systems, the materials used in construction projects should be certified, and the components need to be declared.

In this literature review, construction codes, regulations, standards and policies from different state DOTs were also discussed. Energy efficiency, materials declaration, and proper waste management were the major focus areas. Among the reviewed state DOT policies, the state of Washington enforces RCW 39.35D.030 “High Performance Green Building” to make sure statefunded projects meet the LEED silver standard. The state of California enforces the Green Building Standard Code to provide guidelines for sustainable construction. The state of Oregon requires the state-owned facility to follow SEED rules and LEED guidelines (Department of Administrative Services, 2004; Oregon Department of Transportation, 2012). In fact, the state of Oregon has required, since 2004 that all construction and/or renovation projects for a facility built using state funds should be at least LEED Silver certified. Current case studies indicated that solar, wind, and geothermal energy sources are commonly used in recently-built maintenance stations incorporating sustainable design elements. In addition, advanced waste management plans were also commonly implemented at many DOT maintenance stations.

Both LCA and LCCA were used in this current project to evaluate the energy efficiency, cost effectiveness, and other environmental related performances of two ODOT maintenance stations (case studies) and to develop a best practice guide for the construction of new maintenance facilities. In this project, the focus is on the energy and materials, representing a modified approach to both LCA and LCCA. Recommendations from key green building rating systems, especially practices germane to ODOT, complemented the LCA and LCCA for developing the best practices guide.

3.0 METHODOLOGY

The main goal of this research project is to produce a Best Practices Guide that provides ODOT, and its architects, planners, designers, and builders, with up-to-date information on current efficient, cost-effective, and sustainable construction practices to support more informed decision making. To achieve this goal, we proposed an approach that relies on a modified life cycle assessment (LCA) and a modified life cycle cost analysis (LCCA) for two existing ODOT maintenance facilities (in Albany and Sisters). The Albany maintenance facility is a traditional maintenance facility, while the Sisters maintenance facility was constructed more recently, considering use of a renewable energy sources and other sustainable design practices. Given the timeline and budget for the project, the focus of the LCA and LCCA was on energy and materials costs and environmental impacts. This focus aligns with the areas of largest potential cost savings and potential for meeting environmental sustainability goals.

In this study, alternative designs were compared with base cases. The alternative facility designs allowed the research team to determine which design choices result in increased energy efficiency, reduced construction and/or operating costs, and a reduced environmental footprint. These design alternatives formed the basis for the options in the Best Practices Guide developed under this project. The goal was not to produce a single "best" design for a maintenance facility, but rather to provide options, with data support, that will allow for context sensitive solutions when a new maintenance facility is slated for design and construction.

This document provides the detail on the proposed methodology for performing the modified LCA and LCCA for the alternative facility design cases. It also provides information on how the results of the two studies were used to inform the creation of the Best Practices Guide.

3.1 LIFE CYCLE ASSESSMENT (LCA) METHODOLOGY

As introduced above, one of the main objectives of this project is to assess the energy and materials-related environmental impacts for two ODOT maintenance facilities. The methodology undertaken to assess energy and materials use, and related impacts, is based on the ISO 14040 (International Organization for Standardization,2006a) and ISO 14044 (International Organization for Standardization,2006b) guidelines on performing Life Cycle Assessment (LCA), as well as a number of alternative methodologies gathered from literature. These methods were presented in the Draft Literature Review, previously submitted to ODOT under this project. This Methodology Report describes the process of developing a Life Cycle Inventory (LCI) to create a foundational framework for data collection and model inputs for LCA software (SimaPro).

3.1.1 Goal & Scope Definition

3.1.1.1 *Goals*

The objectives of the LCA described in the project agreement (Oregon Department of Transportation & Oregon State University, 2015) sets the goals for this study. These objectives include (1) to conduct a modified LCA focusing on energy and materials for the current maintenance facility in Albany, OR and for the recently constructed Sisters, OR maintenance facility, and (2) to develop a Best Practices Guide that will enable ODOT decision makers and design and building professionals to evaluate the cost and environmental performance of options for new construction or reconstruction/remodeling of existing maintenance facilities. The Best Practices Guide will also provide supporting design guidance for improving facility efficiency, cost-effectiveness, and sustainability, by focusing on energy and materials use across the life cycle.

In addition, the results of this LCA study could be used to support policy decisions related to the environmental issues that government agencies, such as ODOT, are currently facing. Recent adoption of building certifications by ODOT and other agencies, such as Leadership in Energy and Environmental Design (LEED) (United States Green Building Council, n.d.-b) certification, creates the need for evaluation of different certifications to derive the most appropriate best practices for maintenance facilities.

3.1.1.2 *Scope*

Figure 3.1 displays the methodological steps proposed in this study. A type-zero integrated definition language (IDEF0) is used to help visualize the methodological steps. Two LCA case studies, i.e., “Albany and Sisters LCA,” correspond to activity box A1. The inputs for the two LCA studies are the bill of materials (BOM), building specifications, floor plans, and energy assessment reports produced by the Oregon State University (OSU) Energy Efficiency Center (EEC). Structural and energy saving upgrades made to the Albany maintenance facility were considered in the Albany case as renovation activities. SimaPro LCA software is used to assist the research team in completing the two LCA case studies.

Oregon State environmental laws and guidelines were considered throughout the project. The new maintenance facility in Sisters, OR was designed to comply with the State Energy Efficient Design (SEED) rules (Oregon Department of Energy, 2007), and also adopted some of the LEED certifications guidelines. This will be considered in the “Sisters” case study. The outputs of the two LCA studies are two sets of LCI/LCIA data on energy and materials use. Substantial energy saving features can be identified based on the LCI/LCIA results and best practices (BP) found in literature, as depicted in box A2. Finally, the team integrated cost analysis from the LCCA portion of this report to produce the final Best Practices Guide most relevant to ODOT by considering appropriate use factors such as climate and geographical characteristics (box A3).

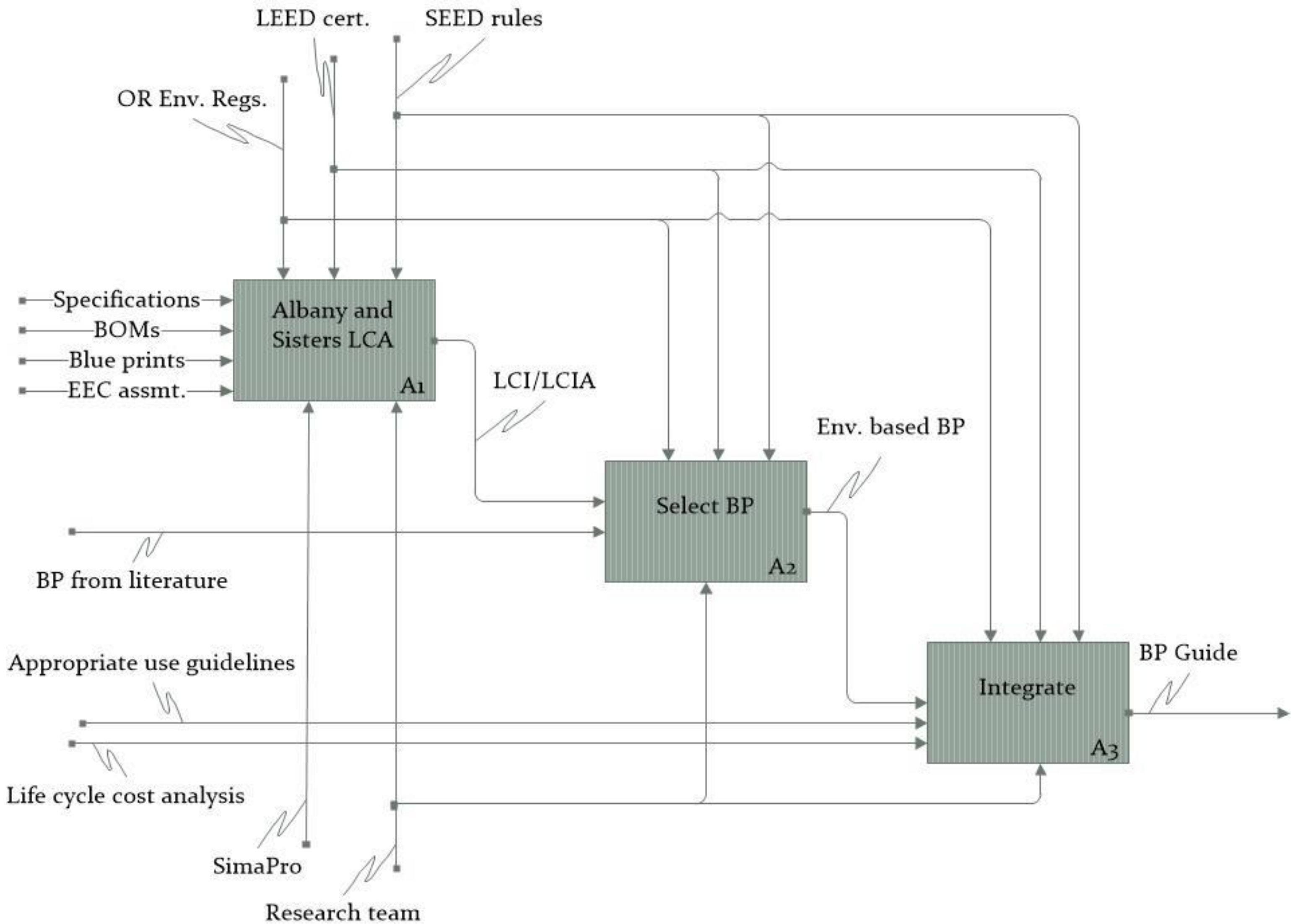


Figure 3.1. Methodology for modified LCA (IDEF0 modeling)

3.1.1.3 *Functional Unit*

The common functional units (FU) used for building LCAs are chosen in terms of energy and environmental releases per area per year (Kneifel, 2010b; Zabalza Bribián, Aranda Usón, & Scarpellini, 2009b). Since the building specifications for the Albany maintenance facility (Turner, Barber, & Barrett, 1995b) and the Sisters facility (GPA Architects LLC, 2011), including the floorplans for each case (GPA Architects LLC, 2012; Turner, Barber, & Barrett, 1995a) use English units for measurement, the FUs for this study are chosen to be ton-CO_2/ft^2 for environmental releases of energy and materials processes in terms of individual components. The single score system (National Institute of Standards and Technology, 2010), which uses points (Pt) as scoring units, is normalized as Pt/ft^2 and used for the purpose of summarizing all impact categories. The same life expectancy is assumed for both buildings for comparison, as discussed below.

3.1.1.4 *Building Life Span*

The building life span for each of the cases (Albany and Sisters) is 50 years, as reported by previous LCA studies (Ghattas, Gregory, Olivetti, Greene, & Hub, 2013b; Zabalza Bribián et al., 2009b). This is also consistent with current greenhouse gas (GHG) reduction goals (Ghattas et al., 2013b), as well as ODOT's projected plan for the Sisters maintenance facility (R&W Engineering, 2015b).

3.1.1.5 *System Boundary and Exclusion*

Table 3.1 presents the typical life cycle of a building (Zabalza Bribián et al., 2009b). SimaPro database already includes recycled and reused materials as well as transportation to suppliers during the production phase; therefore, this information was not inputted into SimaPro as this would cause double-counting. The deconstruction phase should capture the environmental loads of the recycling and reuse process and transportation of waste based on the chosen waste scenario from SimaPro. Due to the scope of the study, operational water use is excluded from the analysis. However, energy for water heating was considered. Maintenance was combined with repair and replacement of building systems, structures, and components, and was not viewed as a separate process.

Table 3.1. Life Cycle Stages of Buildings

Stage	Sub-stage
Production*	Raw Materials Supply
	Transportation
	Manufacturing
Construction	On-site Processes
	Transportation
Management	Maintenance
	Repair and Replacement
	Renovation
	Operational Energy Use
	Operational Water Use**
Deconstruction	Demolition
	Recycling and Reuse
	Transportation
	Disposal

*Excluding recycled/reused materials. ** Not included in the study scope

The investigated structures include those contained within the main buildings, where the offices and primary maintenance bays are located. External structures, such as parking lots, pavement, storage sheds, and landscaping were not considered in the study. As an example, Figure 3.2 shows the as-built (1995) drawing of the Albany maintenance facility (Turner et al., 1995a). Since the focus of this study is on facility design elements and the garage materials and structures are similar to those of the main office buildings, only Building B (main buildings) for both Albany and Sisters facilities were included in the analysis.

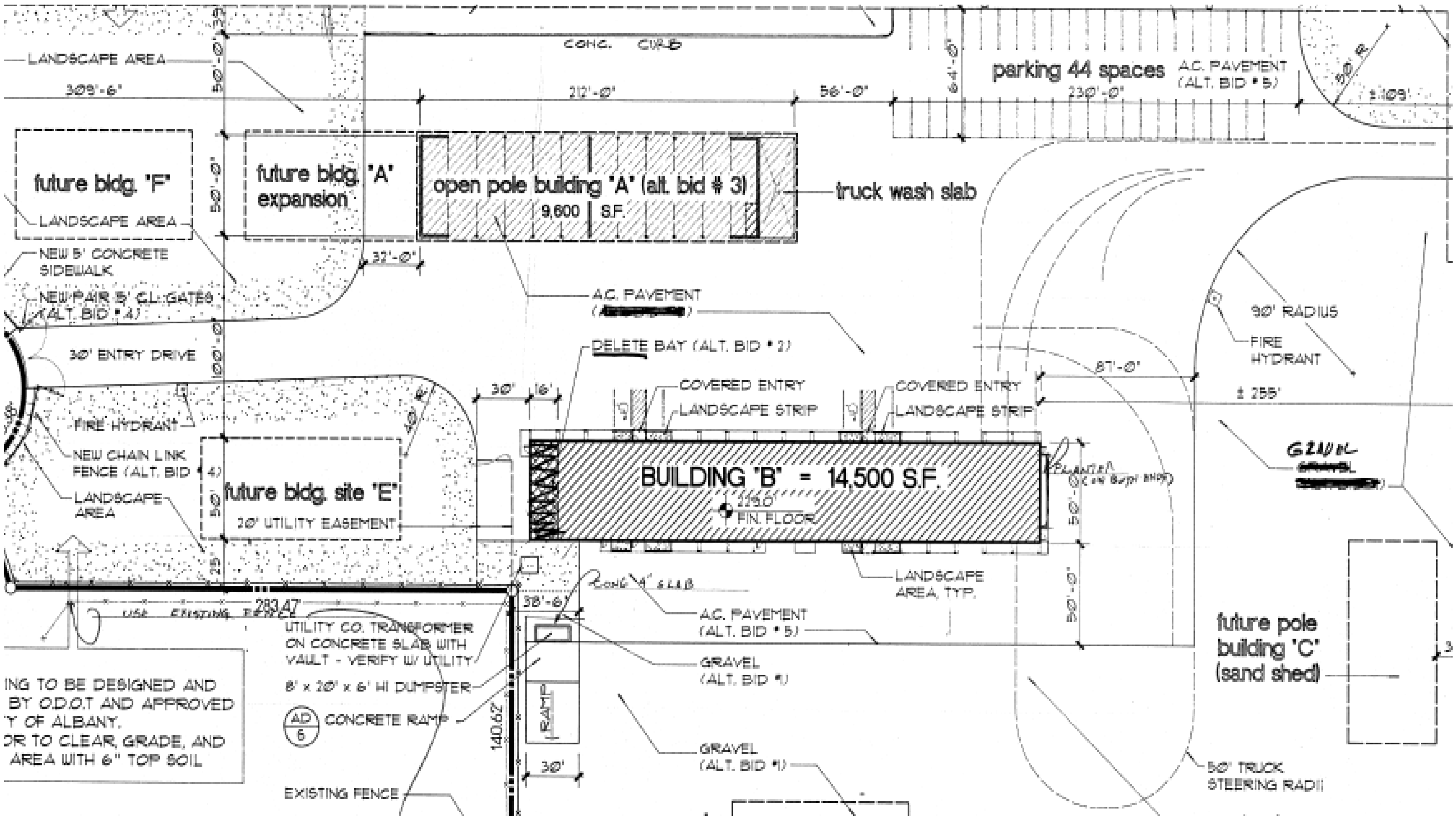


Figure 3.2. As-built drawing of the Albany maintenance station (Turner et al., 1995a)

3.1.2 Life Cycle Inventory (LCI)

The energy use and emissions relevant to the building life cycle result from two sources: (1) electricity, fuels, and materials used during production, transportation, construction, repair and replacement, renovation, and deconstruction of the building, and (2) operational electricity and fuel used during the operations and management stage. Data for (1) was obtained from building specifications and upgrades for the three cases, as well as information and assumptions related to transportation distance, transportation means, standard construction practice, waste management, and recycling/reuse process. Data for (2) was obtained from onsite visits by the research team and analysts from the OSU EEC, e.g., through measurement of operational energy use.

3.1.2.1 *MasterFormat and Building Specifications*

The 1995 Albany maintenance facility building specifications document (Turner et al., 1995b) and the 2011 project specification for the Sisters maintenance facility (GPA Architects LLC, 2011) both follow the MasterFormat standard (CSI, 2014b). These specifications documents provide necessary details on materials and components that make up the buildings. Excluding Division 00 (Procurements and Contract Requirements Process) and Division 01 (General Requirements), the documents provide the framework for data collection of materials and energy inputs for the production, construction, and deconstruction stages. For example, a few items in the building specifications are presented as below:

2.02 Division 03 -- Concrete

A. 03 3000 - Cast-in-Place Concrete

B. 03 4500 - Precast Architectural Concrete

2.03 Division 05 -- Metals

A. 05 5000 - Metal Fabrications

3.1.2.2 *LCA Software (SimaPro)*

SimaPro (PRé, 2016) provides rich databases for construction products and activities. Models of life cycle processes (raw materials acquisition, transportation, construction, etc.) can be developed using the software and the built-in databases. Each component from the building specifications can be entered into the software, together with the required parameters (weight, distance transported, transportation types, etc.). Inputs such as materials, fuels, and energy inputs, as well as outputs such as solid, liquid, and gaseous releases were included in the LCI. Each component and associated processes can be accounted for using the diagram in Figure .

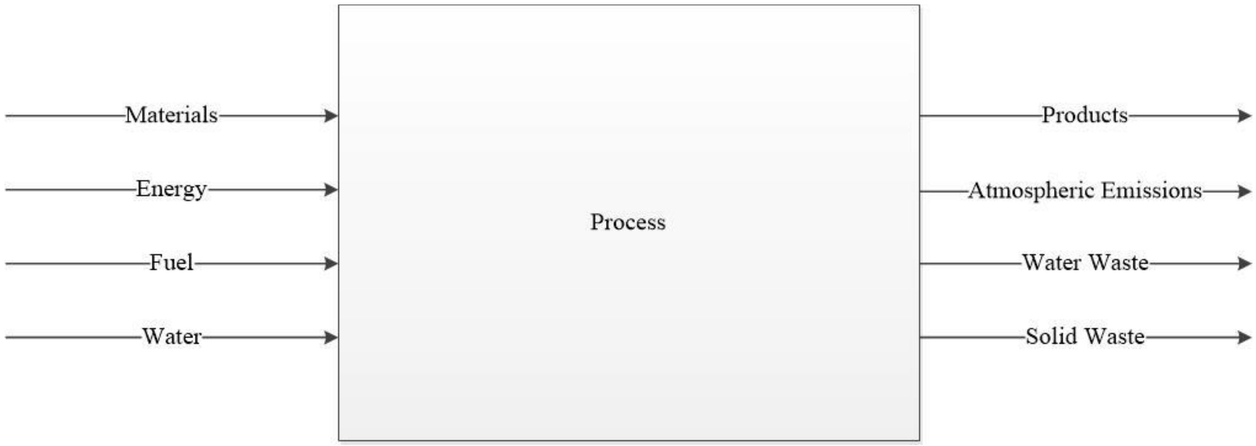


Figure 3.3. Process input and output flow diagram (United States Environmental Protection Agency, 2006b)

3.1.2.3 *Inputs and Quantity Take-off*

3.1.2.3.1 Production, Construction, Renovation, and Deconstruction Stages

First, the team performed a quantity take-off using the buildings' blueprints and specifications to itemize and quantify all components and their associated measurements. Site-specific information was obtained from the building documents and from ODOT personnel during site visits. Organization of the components is based on the MasterFormat. Next, information about the different materials, processes, and parameters (weight, distance, transportation types, etc.) associated with different life cycle stages was input into MS Excel sheets to create LCI that will then be transferred into the LCA software (SimaPro). The list of assumptions on parameters is provided below.

3.1.2.3.1.1. Transportation from plant to construction site

Transportation to construction site is 30 miles. Only transportation of main structural components is considered. The means of transportation is by 32-ton lorry.

3.1.2.3.1.2. Heavy construction equipment

Construction equipment power is 79 kW, based on the average of heavy equipment energy data (Hong Taehoon, Ji ChangYoon, Jang MinHo, & Park HyoSeon, 2014). Diesel was assumed as fuel used for operating construction equipment. Heavy equipment usage time for each task is equal to the estimated labor hours for each task that requires heavy equipment usage. Published construction cost data (Peurifoy, 2008) is used as the main resource for estimating labor hours.

3.1.2.3.1.3. Recyclables

Recyclables only include recyclable materials considered in existing models in SimaPro.

3.1.2.3.1.4. Waste Scenario

U.S. waste types and treatments (US EPA, 2016) data is included as one of the waste scenario models in SimaPro database, and is used as waste scenario for both buildings. If certain materials or processes were not contained in SimaPro's databases, the research team either (1) searched existing literature for the missing information, or (2) made assumptions using a similar material or process that is available in a database. In addition, replacement of parts, systems, and materials will occur during the building life cycle. The suggested number of replacement and renovation of building components (n) can be calculated as shown in Eq. 3-1 (Adalberth,1997):

$$\boldsymbol{n = (life\ of\ building / life\ of\ material) - 1} \tag{3-1}$$

Information on major renovations was obtained from ODOT managers and facility personnel. In this project, only replacement of light bulbs (both buildings) and renovation of second floor (Albany) were considered.

3.1.2.3.2 Operational Materials and Energy Use

The research team coordinated with the OSU EEC and the building managers at each facility for site visits to collect operational materials and energy data. The team first conducted an energy study in Albany to evaluate the energy performance of the building with the incorporated energy efficient upgrades. Some examples of major contributions to energy use include HVAC system, electrical power system, and lighting. Energy use for both buildings was determined using historical data and information collected by the OSU EEC. The Albany station was visited in March 2016 by the research team. The energy assessment site visit was scheduled in June 2016 with the research team and the OSU EEC. The team conducted another energy assessment site visit to the Sisters facility in November 2016, along with the OSU EEC.

3.1.2.4 *Outputs - Emissions, Wastes, and Products/Byproducts*

The LCA software (SimaPro) produces output results based on input values. Outputs include products/byproducts, atmospheric emissions, water, and solid wastes.

Key LCI results can elucidate effects of the production, construction, renovation, and deconstruction stages for insulation materials, concrete, floor coverings, roofing, and external wall structures, for example.

3.1.3 Life Cycle Impact Assessment

The research team presented three examples of LCIA using three different methods – Building for Environmental and Economic Sustainability (BEES) (midpoint) (National Institute of Standards and Technology, 2010), ReCiPe (Goedkoop et al., 2009), and cumulative energy demand (Patel, 2003). Since the focus of this study is on impacts associated with energy and materials, the impact assessment(s) chosen needs to consider relevant and policy-based criteria for ODOT. Therefore, BEES (midpoint) was chosen as the main LCIA method. Based on the most current ODOT sustainability reports (Oregon Department of Transportation, 2016; Oregon Department of Transportation, 2014) and the main focus of this study, i.e., materials and energy, the EPA weighting method was selected.

LCIA was performed in three main stages. The first stage of the interpretation step is to identify the driving forces of impacts. Next, substitution of inputs such as materials, fuels, and transportation modes are carried out individually and in combination to observe saving potentials. Finally, final recommendations are presented based on factors specific to ODOT such as appropriate uses and environmental management plans and regulations.

To further assist ODOT in choosing design option for energy saving, Appendix C and D present suggestions for alternative building structures and energy systems, respectively. The suggestions include their appropriate uses, energy efficiency features, environmental impacts, and cost information. The information in Appendix C and D was obtained from literature and past best practices guides. The OSU EEC provided assistance in collecting the information.

3.1.4 Uncertainty Analysis of LCA in SimaPro

SimaPro uses Monte Carlo analysis to analyze the variation in the results based on pre-assigned distributions of the data (PRé, 2016, Chapter 9). Distributions of data during material acquisition, production process, and disposal were built in the software's database. Parameters during the construction, operation (energy use and replacement of parts), and transportation from suppliers to construction site were input as constants.

Uncertainty analysis of the life cycle impacts of the main building structures and comparison of the two facilities were performed using SimaPro.

3.2 LIFE CYCLE COST ANALYSIS (LCCA) METHODOLOGY

3.2.1 Objectives

Life cycle cost analysis (LCCA) can be used to estimate the total cost of facility ownership (National Institute of Building Sciences, n.d.). LCCA can be used to maximize the life cycle savings by evaluating alternatives that can fulfill the same project requirements. Thus, LCCA can be used to compare the life cycle costs of design alternatives. In this study, the life cycle cost of the two maintenance facilities and potential alternatives are investigated. The LCCA study focuses on construction/procurement and the operations/maintenance costs. The results include the total life cycle cost as well as the estimated payback period for various alternatives. Additionally, the results of the LCCA, combined with those from the LCA, help reveal the most efficient, cost-effective, and sustainable options under different scenarios (e.g., geographic location). These results are documented in the Best Practices Guide for future reference by ODOT personnel and others. The information will assist decision makers in making design choices and selecting the most appropriate materials, technologies, or systems.

3.2.2 Analytical Process

A commonly used LCCA process was described in previous studies (Fabrycky & Blanchard, 1991), as shown in Figure 3.4. In general, after a problem is defined and design alternatives are selected, a break-down analysis is done. Several categories are selected, including construction cost and operation cost, to aid decision making based on project requirements. After these major categories are set, relevant sub-categories are identified and listed. For example, utilities costs would be a sub-category of the operation cost category. The sub-categories need to be as inclusive as possible.

In this study, the break-down analysis was completed to maintain alignment with the LCI categories in the LCA study. After all sub-categories were identified, the cost analysis was carried out by using selected cost models and supporting calculation tools. After calculating costs, high-cost contributors were identified from among the set of alternatives. Thus, more robust recommendations could be reported in the Best Practices Guide.

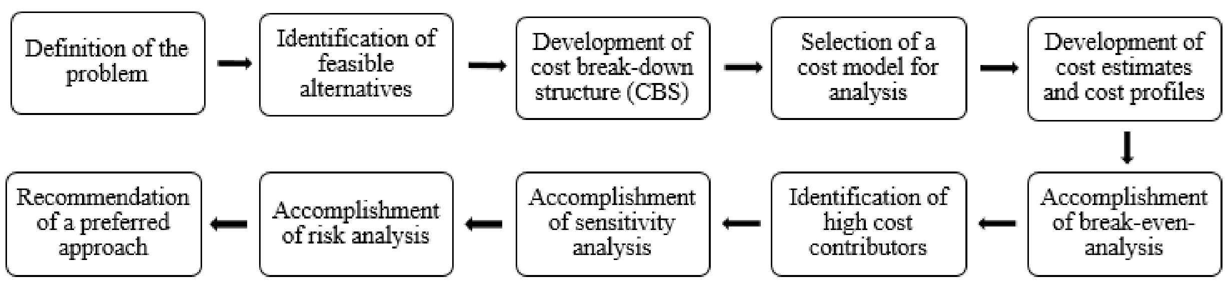


Figure 3.4. LCCA process adopted from previous research (Fabrycky & Blanchard, 1991)

3.2.3 Information Gathering

To successfully complete an LCCA, information (e.g., model parameter values) to calculate various costs need to be acquired before conducting the cost analysis. Cost information includes the construction cost, fuel cost, operation cost, maintenance cost, residual cost, and financial charges. The construction cost and operation cost are the main focuses of this study. The information was obtained through four major paths: ODOT documents, site visits, and data collected by the OSU EEC, and from literature, as discussed briefly below.

In general, the data acquisition plan as discussed above is listed in Table 3.2.

Table 3.2. Data Acquisition Plan

Construction cost*	ODOT specifications and drawings (bidding documents)
Operation cost*	ODOT financial reports, OSU EEC reports, site visits, literature
Maintenance cost	Site visits and OSU EEC reports
Residual cost	Assumed to be negligible
Fuel cost	BLCC-5 database (United States Department of Energy, n.d.-a)
Financial charges	ODOT financial reports

*Main focus of the study

3.2.4 ODOT Documents

The project specifications and drawings provided by ODOT include information about the structure, materials requirements, and quantities. Construction costs incurred during design and construction was obtained from the bidding documents and contractor reports to ODOT.

3.2.5 Site Visits

Site visits were conducted for each maintenance station to accomplish the following objectives: 1) investigate usage patterns of the maintenance stations and the various systems; 2) investigate the operational energy efficiency of the equipment; 3) investigate the types of materials and wastes and treatment methods; and 4) gather available cost information (e.g., construction, operation, and maintenance) and other qualitative information that could be useful to the LCA and LCCA studies. Some costs were estimated based on the occupancy frequency and operational efficiency of the equipment, for example.

3.2.6 OSU EEC Report

The OSU EEC assisted the research team to investigate the operational uses and efficiencies of the various systems and equipment, including the HVAC system, lighting, and other energy loads at both Albany and Sisters facilities. The energy analysis reports for both facilities can be found in Appendix E and F. The OSU EEC reports, along with the utility bills provided by each maintenance facility were used to evaluate the operation cost.

3.2.7 Assumptions

To successfully assess the life cycle cost of both maintenance facilities and their alternatives, a few assumptions were made according to current building codes, literature, and other similar studies, and include those mentioned below.

3.2.7.1 *Study life*

The study life refers to the period during which the costs of concern occur. The study life considered here is the life span of the buildings investigated. According to ODOT, maintenance facilities are expected to serve for at least 50 years. Therefore, the expected life (study life) for both buildings is 50 years, from the service date. The planning and construction (P/C) period for Albany building is three (3) years, while P/C spans 3.5 years in the case of the Sisters facility.

3.2.7.2 *Time value of money, discount rates, and escalation rates*

Expenses that have occurred or are expected in the future are included in the LCCA study. The total monetary amounts are converted to a present value (for an assumed base year, i.e., 2016). For example, the costs incurred in constructing the Albany maintenance facility in 1995 were adjusted for inflation from 1995 to 2016. A similar analytical method was applied to the analysis of the Sisters maintenance facility, by adjusting costs from the time they were incurred to the base year (2016). Since cost data obtained from ODOT was presented in current dollars, i.e., inclusive of inflation rate. The current dollars analysis was used to analyze all costs.

The discount rates used are the 2016 OMB discount rates (Fuller and Peterson, 1995), which depend on the purpose of the analysis and the study life(s) being considered. The general discount rate for projects over a 30-year life-span is 3.5%, according to the list of OMB discount rates for 2016.

The escalation rate for each cost entry is assumed to be equal to the 2016 OMB discount rate corresponding to the length-of-study calculated based on the time the cost occurred from the service date. For example, the escalation rate used for a cost incurred three years after the service date would be equal to the discount rate for a length-of-study equal to three years, i.e., 2%. The escalation rate for annually recurring costs is 3.5%.

3.2.7.3 *Site selection*

Site selection is an important factor that could influence the LCCA. Incorporating site selection in LCCA can be complicated (Stanford University, 2005). For the maintenance facilities to be evaluated, site selection limitations did apply before construction, but these considerations are outside the scope of this study.

3.2.7.4 *Average annual replacement cost*

Based on the cost information provided by ODOT, the replacement cost is coded as Objective (OBJ) 290 by ODOT. Figure 3.5 shows the histogram of the OBJ 290 cost per year from 1996-2015 for Albany facility. The present values of these annual OBJ 290 costs were converted to 2016 dollars (PV16.sum.yr290). Most annual replacement costs fell between $0 and approximately $2000; therefore, the annual replacement cost is assumed to be $2000 in 2016 dollars. Annual replacement cost for the Sisters facility was assumed to be the same as Albany, as the building was only in service for three years at the time of this study. Therefore, sufficient historical cost data was not available.

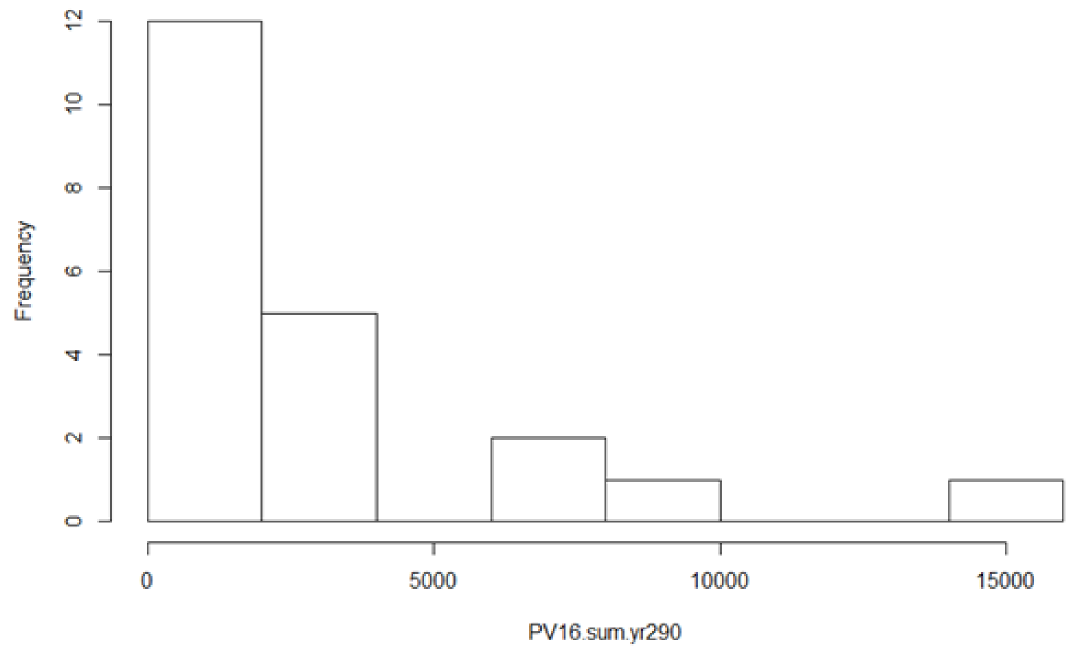


Figure 3.5. Histogram of annual replacement cost (OBJ 290) for Albany, 1995-2015 based on 2016 present value

3.2.7.5 *Major renovation costs*

Figure 3.6 shows the plot of annual OBJ 290 cost. Renovation cost is estimated by subtracting $2000 from the annual OBJ 290 cost whose values exceed $2000. These costs are then compared to history of major renovation events for confirmation. Renovation is considered as one-time cost and converted to 2016 dollars. This study assumes the Sisters facility will only incur annual replacement costs and no major renovation costs.

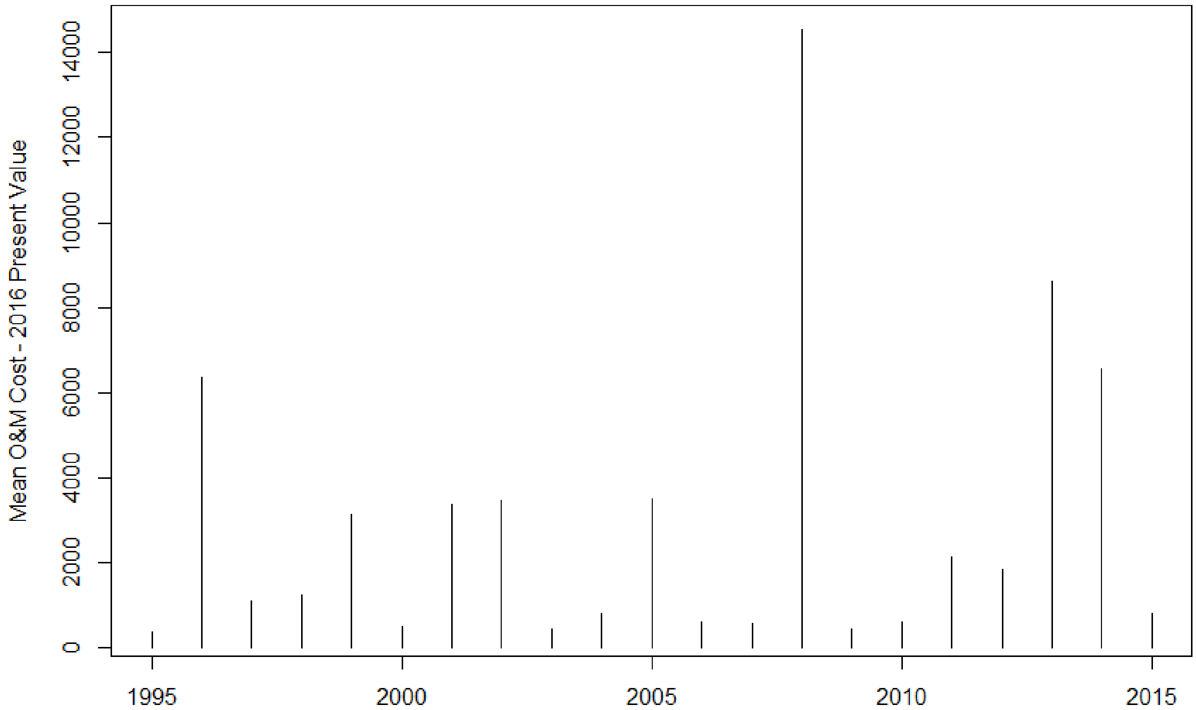


Figure 3.6. Annual maintenance and structural cost for the Albany facility

3.2.7.6 *Operational costs*

Operational and maintenance related costs are selected from the operational budget reports provided by ODOT. Only costs related to the operational and maintenance of the structures are considered. The OBJ list for the annually recurring costs is provided below.

OBJ 270 – Disposal Services

OBJ 281 – Janitorial

OBJ 290 – Maintenance/Structural

OBJ 297 – Housekeeping supplies

OBJ 450 – Hardware/Electric

OBJ 472 – Building material/Facilities

OBJ 576 – Security services

OBJ 951 – Depreciation

The OBJ list for the non-annually recurring costs is provided below.

OBJ 267 – Licenses/Permits

OBJ 289 – Grounds Maintenance

OBJ 294 – Plumbing Services

OBJ 295 – Building/Structure Equipment Repair

OBJ 296 – Power/HVAC Repair

OBJ 314 – Fence

OBJ 408 – Portland cement

OBJ 420 – Bars, post, pile

OBJ 438 – Wood limber post

OBJ 440 – Paint

OBJ 574 – Inspection

OBJ 557 – Security alarm

OBJ 570 – Equipment lease

OBJ 578 – Miscellaneous equipment

3.2.7.7 *Estimation of annually recurring costs*

Annually recurring costs can vary each year; therefore, for each cost category they are estimated by taking the average of the annually recurring costs in 2016 dollars, up to 2015.

Appendix G contains the detail of all inputs for the LCCA performed by BLCC-5.

3.2.8 Evaluation of Total Cost

3.2.8.1 *Methods to Estimate and Compute Life Cycle Costs*

With cost information gathered from across the facility life span, the life cycle cost (LCC) can be calculated as a present value in the base year selected by using Eq. 3-2 (Stanford University, 2005):

$$\mathbf{LCC = C + PV_{recurring} + PV_{non\text{-}recurring} - PV_{residual\text{-}value}} \quad \textbf{(3-2)}$$

Where:

C is construction costs adjusted for the year 0 (the year construction started);

$PV_{recurring}$ is the present value of all recurring costs; and

$PV_{non\text{-}recurring}$ is the present value of the non-recurring costs; and

$PV_{residual\text{-}value}$ is the present value of the residual value at the end of the life span.

$PV_{recurring}$ consists of construction and operation costs that occur periodically, e.g., on an annual basis, while $PV_{non\text{-}recurring}$ consist of improvement, repair, and renovation costs. $PV_{residual\text{-}value}$ is usually assumed to be zero in most studies (Stanford University, 2005). In general, it is most important to calculate the present value (PV). Therefore, the discount rate and escalation rate should be taken into consideration for conversion of the value.

3.2.8.2 *Methods to Estimate Present Value*

The calculation of PV can be described by Eq. 3 (Stanford University, 2005):

$$\mathbf{PV} = \frac{\mathbf{F_y}}{(\mathbf{1+DISC})^{\mathbf{Y}}} \tag{3-3}$$

Where:

PV is present value;

F_y is value at year Y; and

DISC is the discount rate.

Additionally, the influence of price escalation can be accounted for by using Eq. 3-4 (Stanford University, 2005):

$$\mathbf{COST_{Y-year}} = \mathbf{COST_{0-year}} \times (\mathbf{1} + \mathbf{ESC})^{\mathbf{Y}} \tag{3-4}$$

Where:

$COST_{Y\text{-}year}$ is the cost in year Y;

$COST_{0\text{-}year}$ is the cost in year 0; and

ESC is the escalation rate.

Detailed information about discount rate and escalation rate can be found in the Life-cycle Costing Manual for Federal Energy Management Program (Handbook 135) (Fabrycky & Blanchard, 1991).

3.2.9 Calculation Tool

The Building Life Cycle Cost (BLCC) program developed by the National Institute of Standards and Technology (NIST) was used to calculate the life cycle cost.

By using the BLCC program, the user can input all different types of cost as well as the discount and escalation rates. Escalation rate can be calculated by using the Energy Escalation Calculator (EEC) developed by NIST (United States Department of Energy, n.d.-a). Information about the discount rate and escalation rate can be found in the Handbook 135 and annual supplements (S. K. Fuller & Petersen, 1996; Lavappa, 2015). The latest version, BLCC-5, includes different modules for different types of projects, which improves calculation accuracy. The BLCC-5 program is a powerful tool to calculate net savings of the alternative, saving-to-investment ratio, adjusted internal rate of return, and payback period. Figure 3.7 shows the BLCC user interface. The theory BLCC development can also be found in the DOE's LCC Handbook and Handbook 135 (United States Department of Energy, 2014; S. K. Fuller & Petersen, 1996).

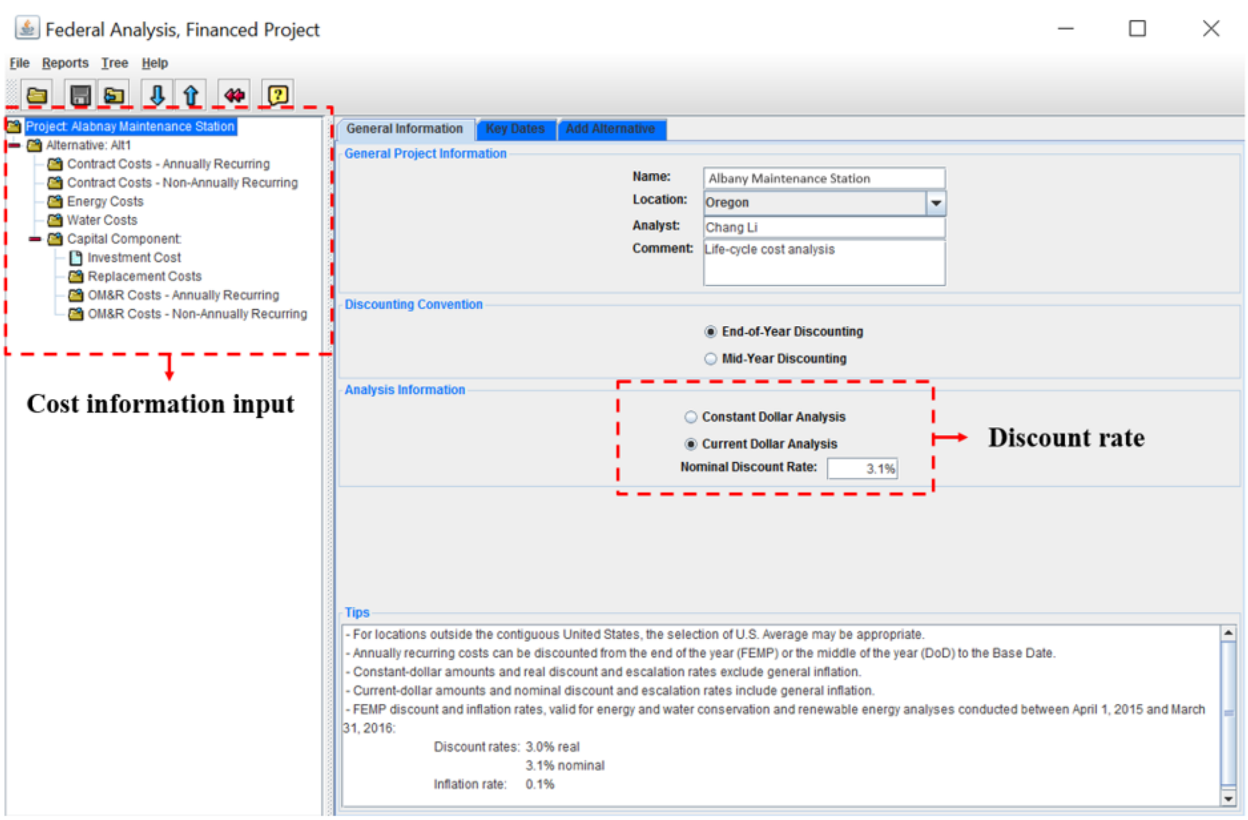


Figure 3.7. BLCC graphical user interface (United States Department of Energy, n.d.-a)

3.2.10 Interpretation of Results

3.2.10.1 *Reporting of the Results*

Through the analysis of both maintenance facilities, the research team was able to identify the advantages and disadvantages of different materials and technologies currently used in the facilities. The life cycle cost was reported for each alternative design. The most cost-effective materials and technologies were included in the Best Practices Guide, along with the most efficient and sustainable options found in the LCA study.

3.2.10.2 *LCA and LCCA*

LCCA is focused on defining the economic/financial benefit of a material, technology, or system, whereas LCA is focused on defining relevant the environmental impacts and relative environmental performance of various alternatives. Research indicated that economic aspects of decisions are seldom addressed through LCA (Norris, 2001). Therefore, conflicts may arise between the results of LCA and LCCA, necessitating decision trade-offs to be made. Through the modified LCA and LCCA, the research team was able to report on both environmental and economic performance for the materials, technologies, and systems evaluated. Trade-offs can then consider local laws, codes, and regulations to facilitate building design decisions.

3.3 SUMMARY

The proposed methodologies for conducting the modified life cycle assessment (LCA) and modified life cycle cost analysis (LCCA) are presented in the foregoing. The Albany maintenance facility was assessed as the base case, since it followed conventional facility design methods. Alternative materials, technologies, and systems were also assessed for their positive and negative influence on environmental impacts and life cycle cost by examining changes at the Albany facility. In addition, investigation of the Sisters maintenance facility was used to assess how new energy sources and other technologies can impact the environmental and economic performance of a maintenance facility. Besides the traditional data gathering methods (discussions with ODOT personnel and literature review), the research team cooperated with the Energy Efficiency Center at Oregon State University to provide more detailed analysis of operational energy use through onsite data collection.

The deliverables from each study are also provided in this document. These include documentation of the methods and results of the LCA and LCCA studies for each of the cases, a report of findings from the OSU EEC, and a Best Practices Guide to assist ODOT personnel in designing and renovating maintenance facility buildings based on findings from the studies.

4.0 RESULTS

4.1 LIFE CYCLE ASSESSMENT

The overall environmental performance for both buildings in terms of single score (kPt) is presented in Figure 4.1. Recall that the single score system (National Institute of Standards and Technology, 2010), uses points (Pt) as scoring units after different impacts categories have been characterized, normalized, and assigned weights. These scores are normalized by the building's area as Pt/ft^2 and used for the purpose of summarizing all impact categories.

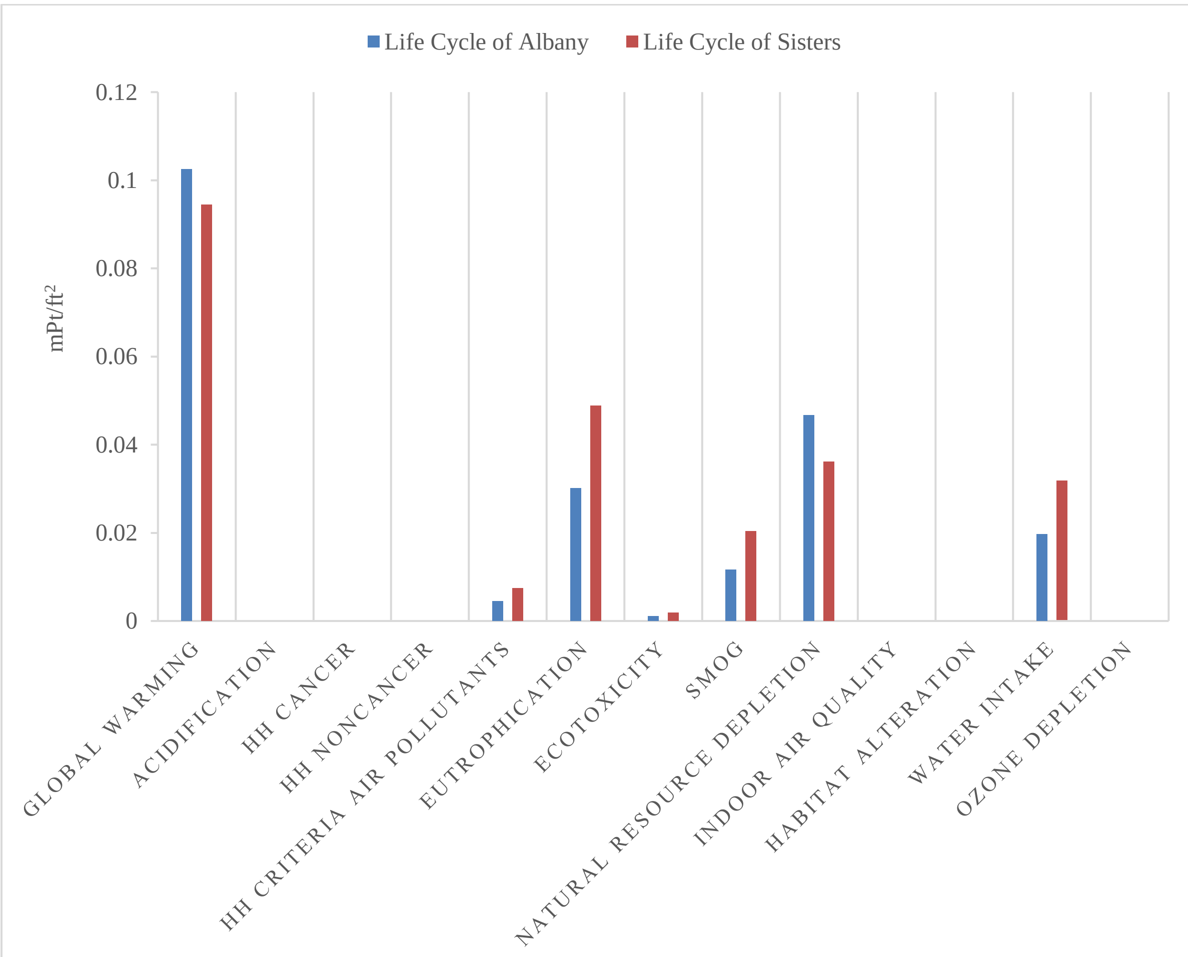


Figure 4.1. Single score performance for Albany and Sisters facilities

Overall, the Sisters facility performs better than the Albany facility in terms of total single score (Pt/ft^2) impact assessment (National Institute of Standards and Technology, 2010). Specifically, Global Warming and Natural Resource Depletion performances see significant improvement in the Sisters facility case. In other impact categories, performances seem to be similar for both buildings. Based on this result, the areas that can benefit from additional efforts of impacts reduction are Global Warming, Human Health Air Pollutants, Eutrophication, Smog, Natural Resource Depletion, and Water Intake.

Comparison in terms of total score for the energy systems, and requisite materials in the energy systems used in both buildings are shown in Figure 4.2.

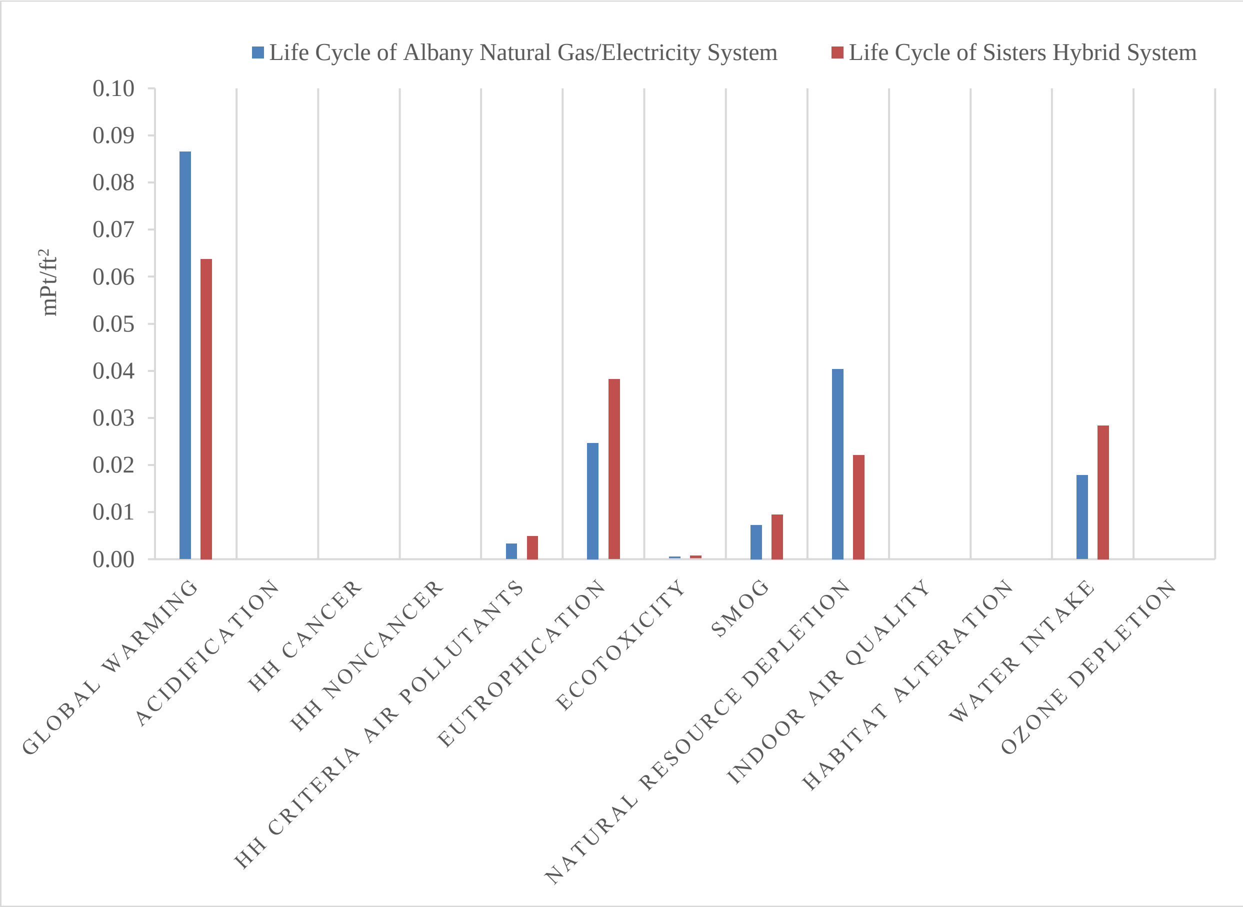


Figure 4.2. Single score performance for energy systems of Albany and Sisters

The single score performances of the energy systems in Figure 4.2 exhibit a similar behavior to that of the buildings presented in Figure 4.1. Energy systems contribute significantly to the total impacts. Global Warming and Natural Resource Depletion see even more sharply reduced impacts in the case of Sisters' energy system.

Figure 4.3 shows the single score environmental performance of the structural components for both buildings.

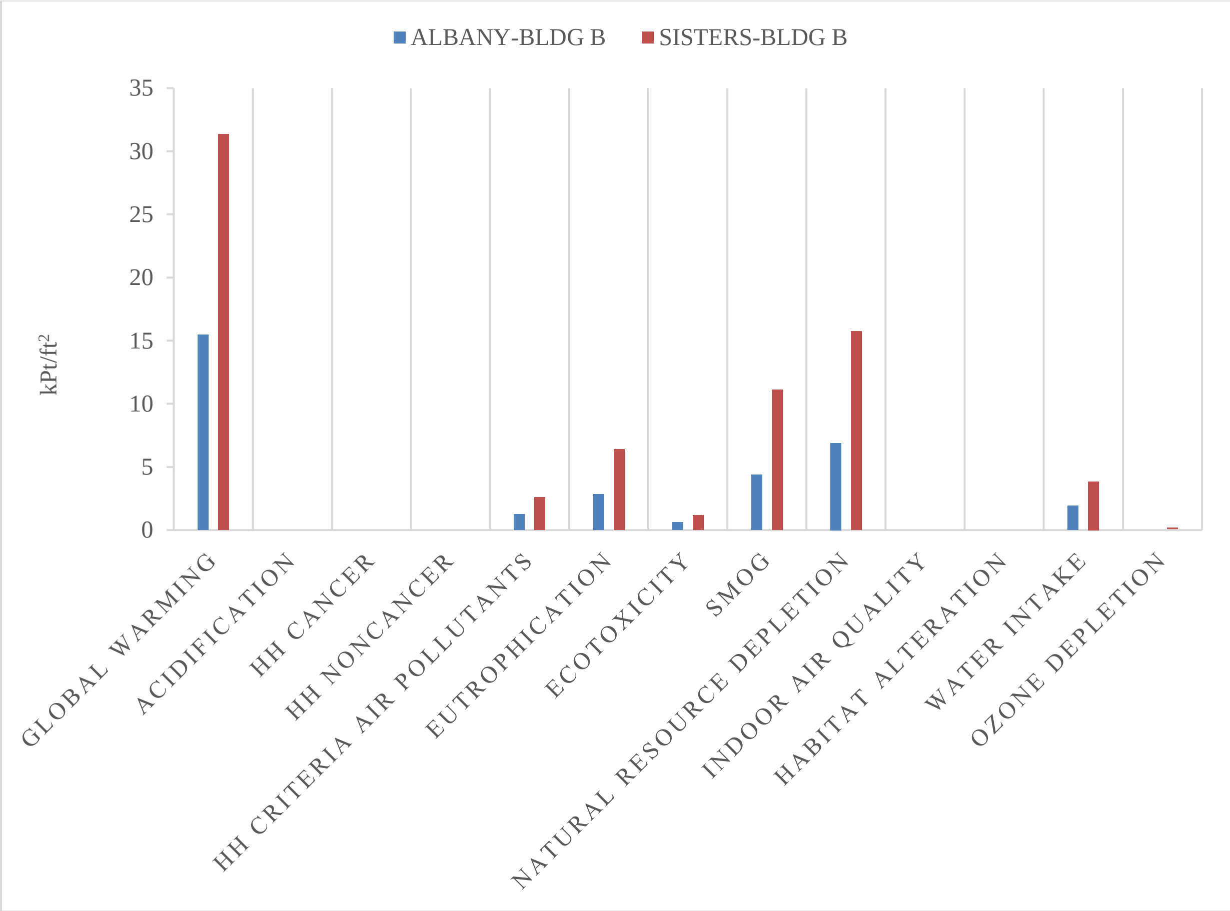


Figure 4.3. Single score performance for structural components of Albany and Sisters

In terms of materials for building structures (operational energy and waste excluded), the Albany facility has better performance in the seven highest impact categories. The structural components of Albany facility perform significantly better in terms of Global Warming, Eutrophication, Smog, and Natural Resource Depletion. However, while performing better in terms of impacts due to structural components, the total life cycle impact of the Albany facility is still considerably higher than the Sisters facility. This illustrates the significant contribution of energy usage over structural materials in building systems.

After assessing impact contributions from energy and materials for both buildings, impacts due to waste treatment for both buildings were considered negligible. In terms of Global Warming Potential (kg-CO_2 eq/ft^2) produced by structural components, the breakdown per sub-component is presented in Figure 4.4.

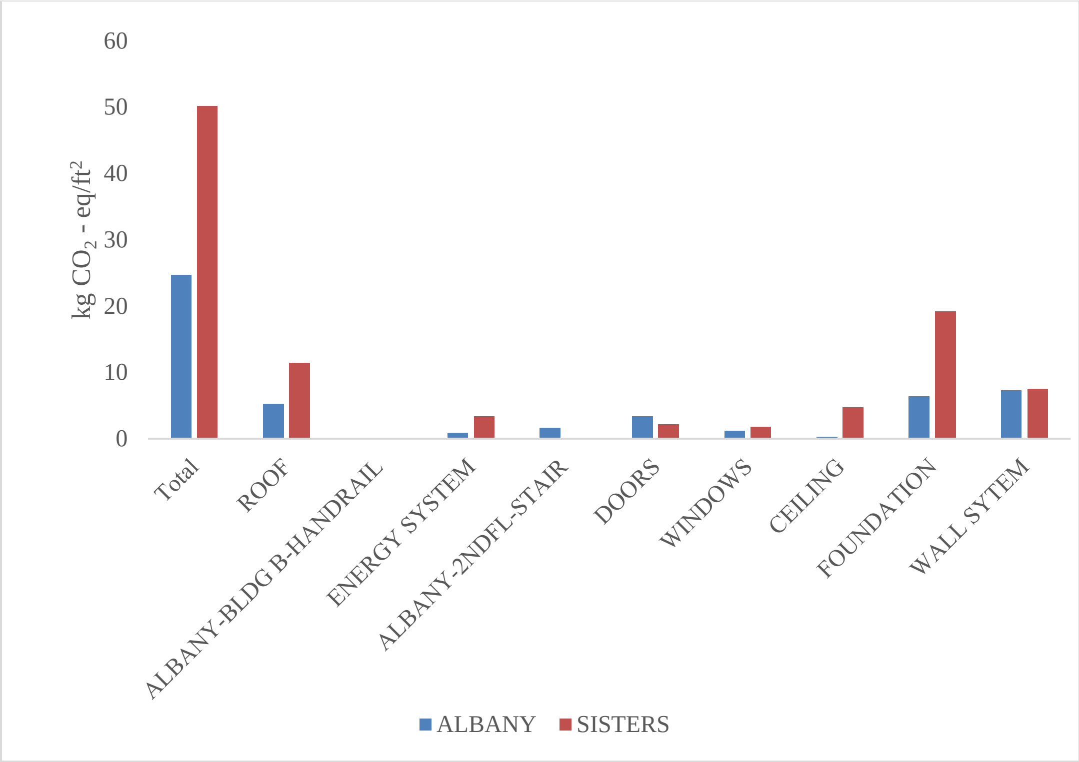


Figure 4.4. Global warming potential by sub-components

Similar to the total impacts due to structural materials shown above, the Global Warming Potential is higher in the case of the Sisters building. The main sub-components with the highest contributions to total Global Warming Potential for Sisters building are the roof, ceiling, foundation, and wall system, and for Albany building are the roof, doors, foundation, and wall system. While the reason for the difference in Global Warming Potential in roofs, doors, ceilings, and wall systems is mainly due to amount of main materials used, such as galvanized steel in the roof. The reason for the difference in Global Warming Potential for the foundation is due to the insulation built into the insulated floor in the case of Sisters building.

In terms of Global Warming Potential per process (>3% contribution), life cycle processes with the highest contributions for Albany (Figure 4.5) and Sisters (Figure 4.6) are presented below.

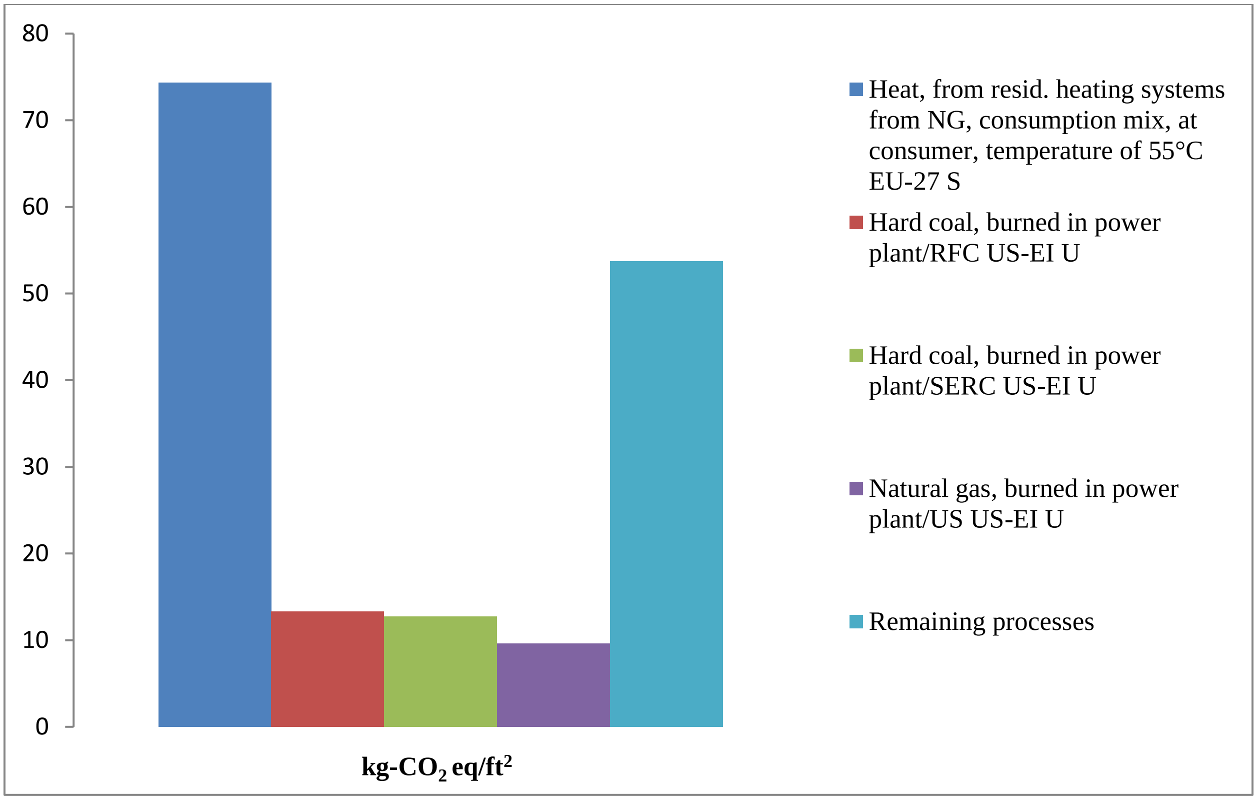


Figure 4.5. Major process contribution to global warming - Albany

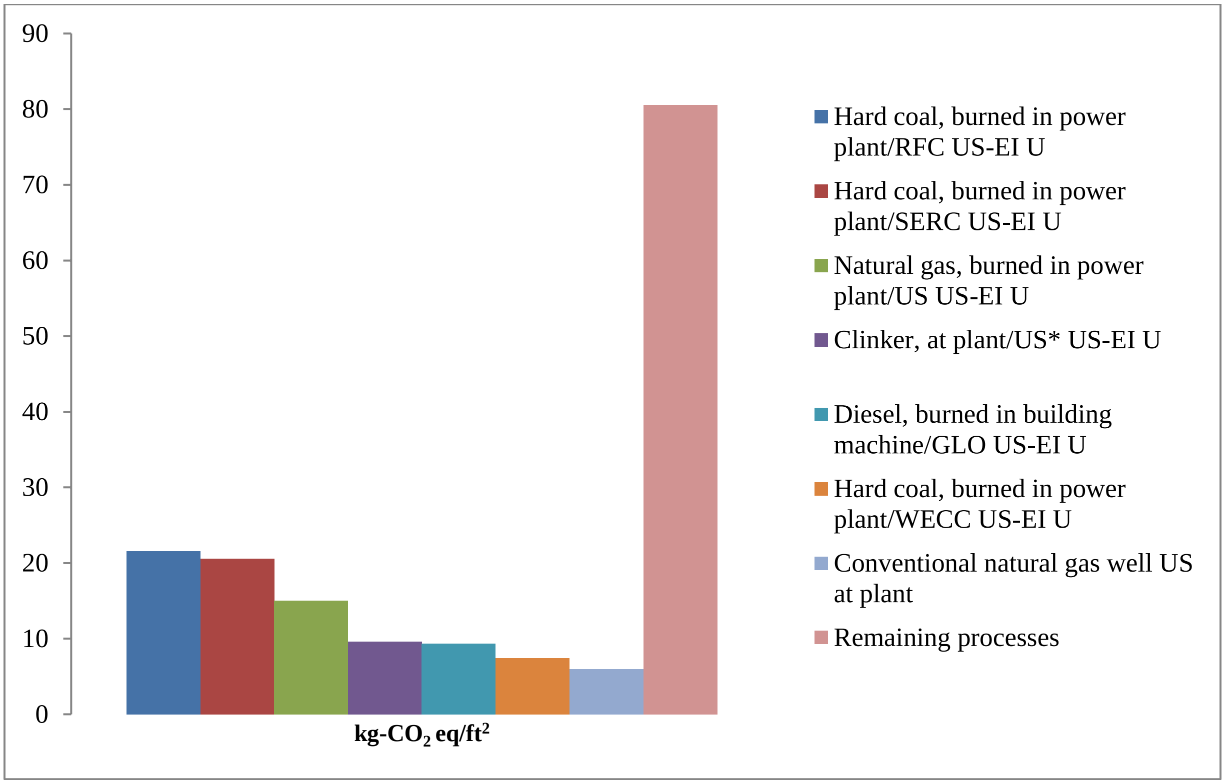


Figure 4.6. Major process contribution to global warming – Sisters

Both figures show the significant impact of energy usage on Global Warming Potential. In the case of Albany, Global Warming Potential from operational natural gas is greater than the combined Global Warming Potential of all remaining process. This makes natural gas a less preferable energy choice for heating than Sister's solar-geothermal system. In the case of the Sisters building, hard coal and natural gas used for production of operational electricity contribute the most to Global Warming Potential. The next highest Global Warming Potential impact contribution results from the production of clinker for concrete.

Allocation of these high-impact processes can help identify the main responsible products or processes and guide decision making during design and construction phases. Further investigation of each building system is presented in the sections below.

4.1.1 Albany Facility

The network of major process contribution (>3%) in terms of Global Warming Potential for Albany is presented in Figure 4.7.

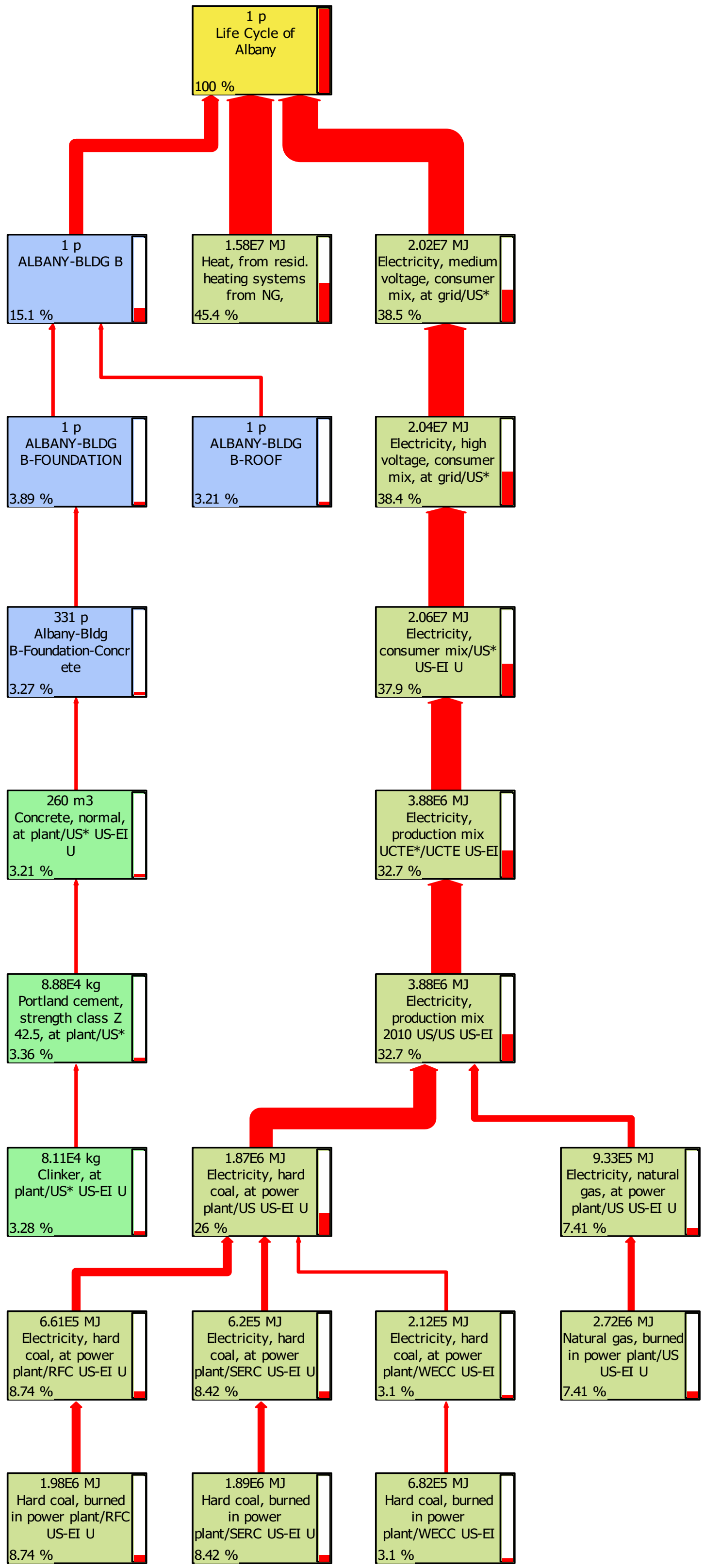


Figure 4.7. Network of process contribution (>3%) in terms of global warming - Albany

While natural gas and electricity for operational uses contribute the most impacts (45.4% for natural gas and 38.5% for electricity), clinker for concrete production is responsible for the highest Global Warming Potential impacts due to the building materials. For this reason, concrete for then foundation and energy system were chosen for further investigation of improved replacements.

4.1.1.1 *Alternative 1 – Replacement of Natural Gas System with a Hybrid System*

Figure 4.8 shows the comparative LCA of the original Albany building and the case of implementing Sisters's solar-geothermal (hybrid) system in Albany.

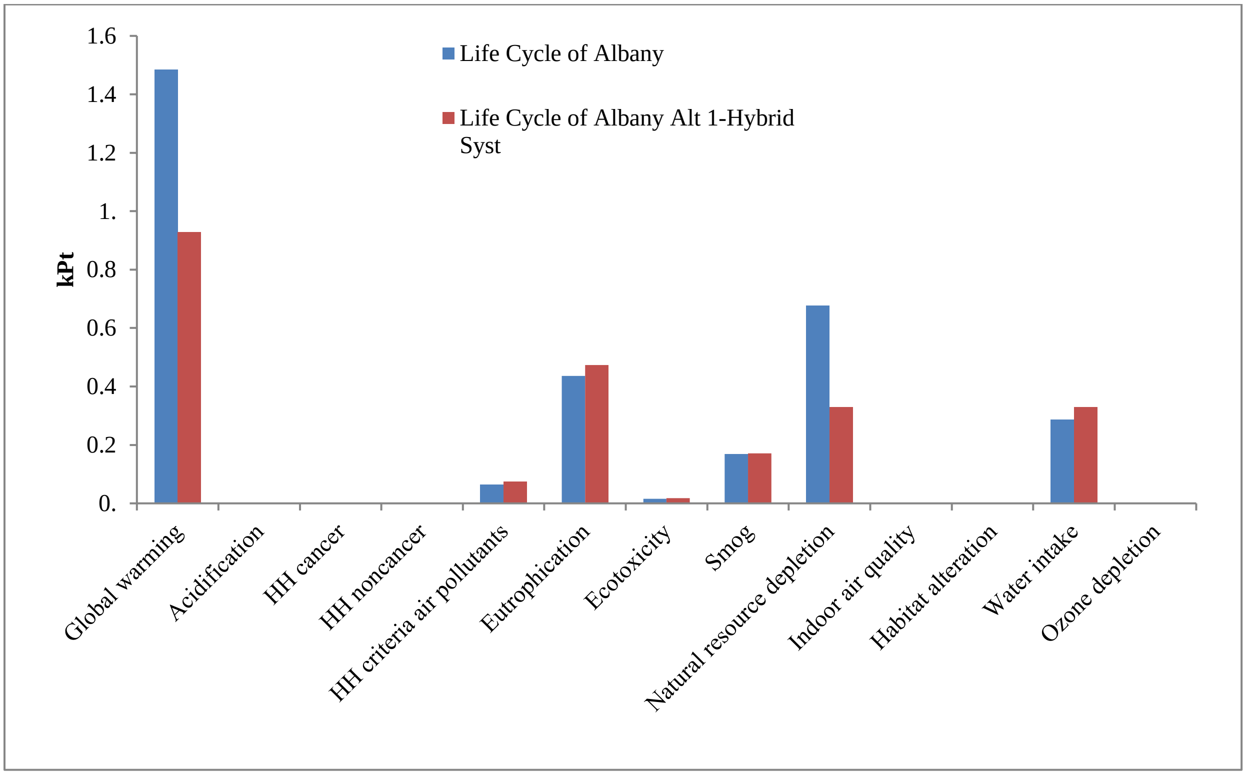


Figure 4.8. Comparative LCA of Albany system and alternative with hybrid system

Material for the hybrid system's equipment and electricity consumption for the alternative case are assumed to be the same as those of Sisters building. This in turn eliminates the use of natural gas for operational energy requirements. Global Warming Potential and Natural Resource Depletion can be significantly reduced, while there are some slight increases in Eutrophication and Water Intake criteria.

Overall, performance of the alternative case in single score terms is significantly improved from that of the original case, as shown in Figure 4.9.

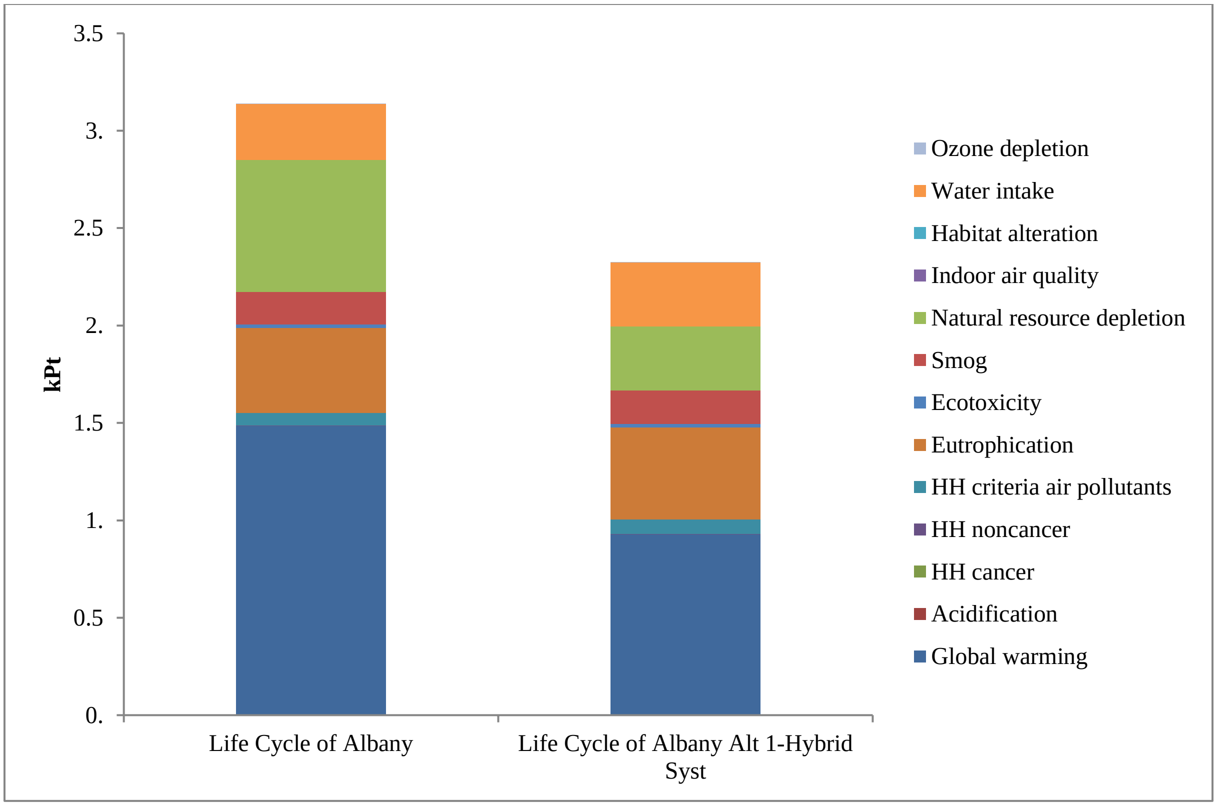


Figure 4.9. Overall performance of Albany with hybrid system compared to original building

4.1.1.2 *Alternative 2 – Replacement of Portland cement Concrete*

Concrete with blast furnace slag cement was chosen as an alternative for normal concrete that uses Portland cement. Both cement options have similar impact categories: Global Warming, Human Health Criteria Air Pollutants, Eutrophication, Eco-toxicity, Smog, Natural Resource Depletion, and Water Intake.

The replacement reduces Global Warming Potential considerably, from 147 mPt to 95 mPt as seen in Figure 4.10, revealing blast furnace cement as a more preferable choice for concrete in terms of environmental performance. Minor impacts reduction can be observed in the Human Health Criteria Air Pollutants, Eutrophication, Eco-toxicity, Smog, and Natural Resource Depletion.

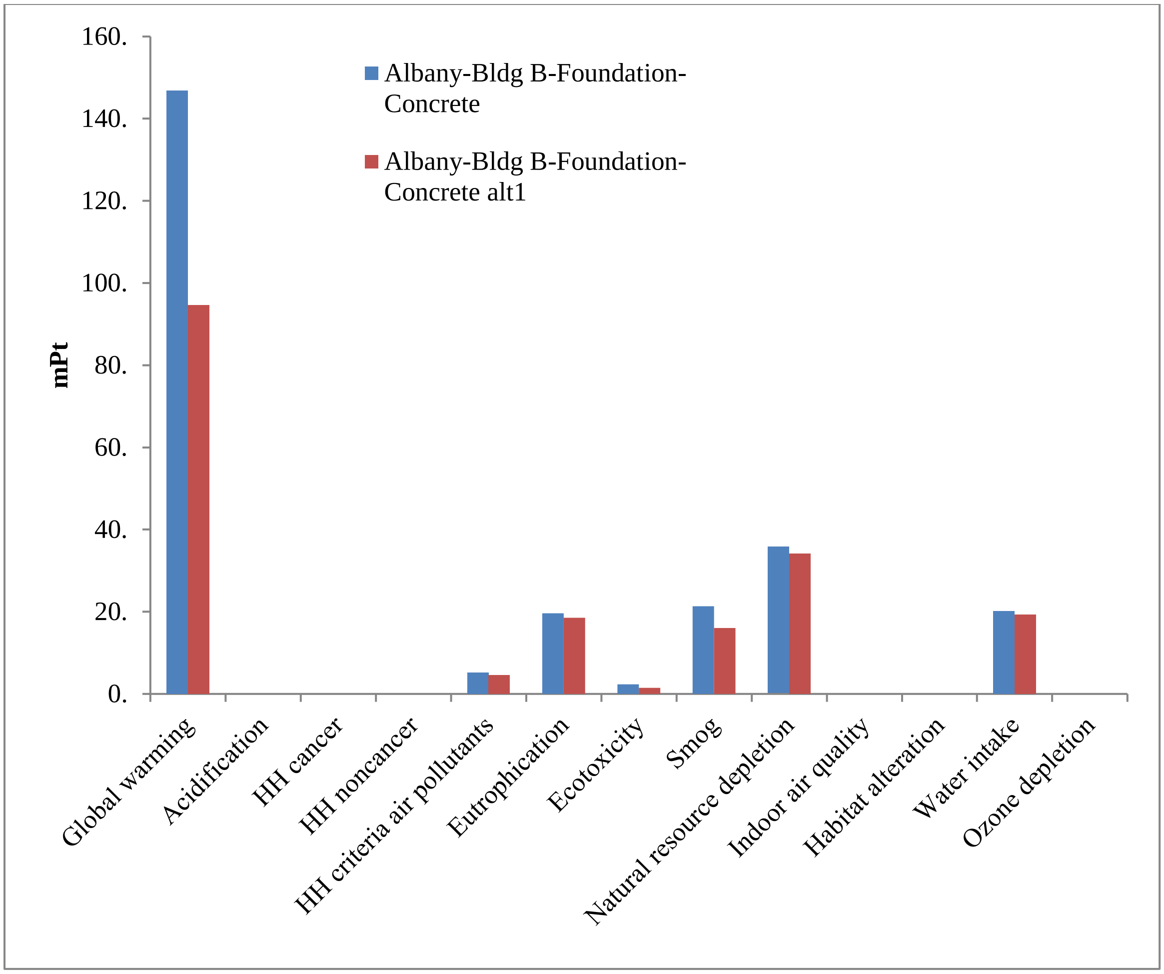


Figure 4.10. Portland cement vs. blast furnace cement (Alt 1) comparison

4.1.2 Sisters Facility

The Sisters building delivers significant improvement in terms of operational energy usage compared to that of Albany building. Closer examination reveals potentials for improvements are closer to those in the Albany case, as shown in Figure 4.11. Proposals for changes in other processes, i.e., diesel burned in construction equipment and electricity production, are outside the scope of this project. An alternative to reduce impacts from concrete production has been proposed in the previous section for Albany.

Diesel used in construction machines causes the third largest contribution to Global Warming Potentials for both buildings, after operational energy production and consumption, and concrete. Diesel use at construction sites has been known to produce the most air emissions of all construction-related energy uses (Sharrard, Matthews, & Roth, 2007). Maintenance of equipment and use of cleaner fuel are among some methods to reduce the impacts of diesel emissions (United States Department of Energy, 2017).

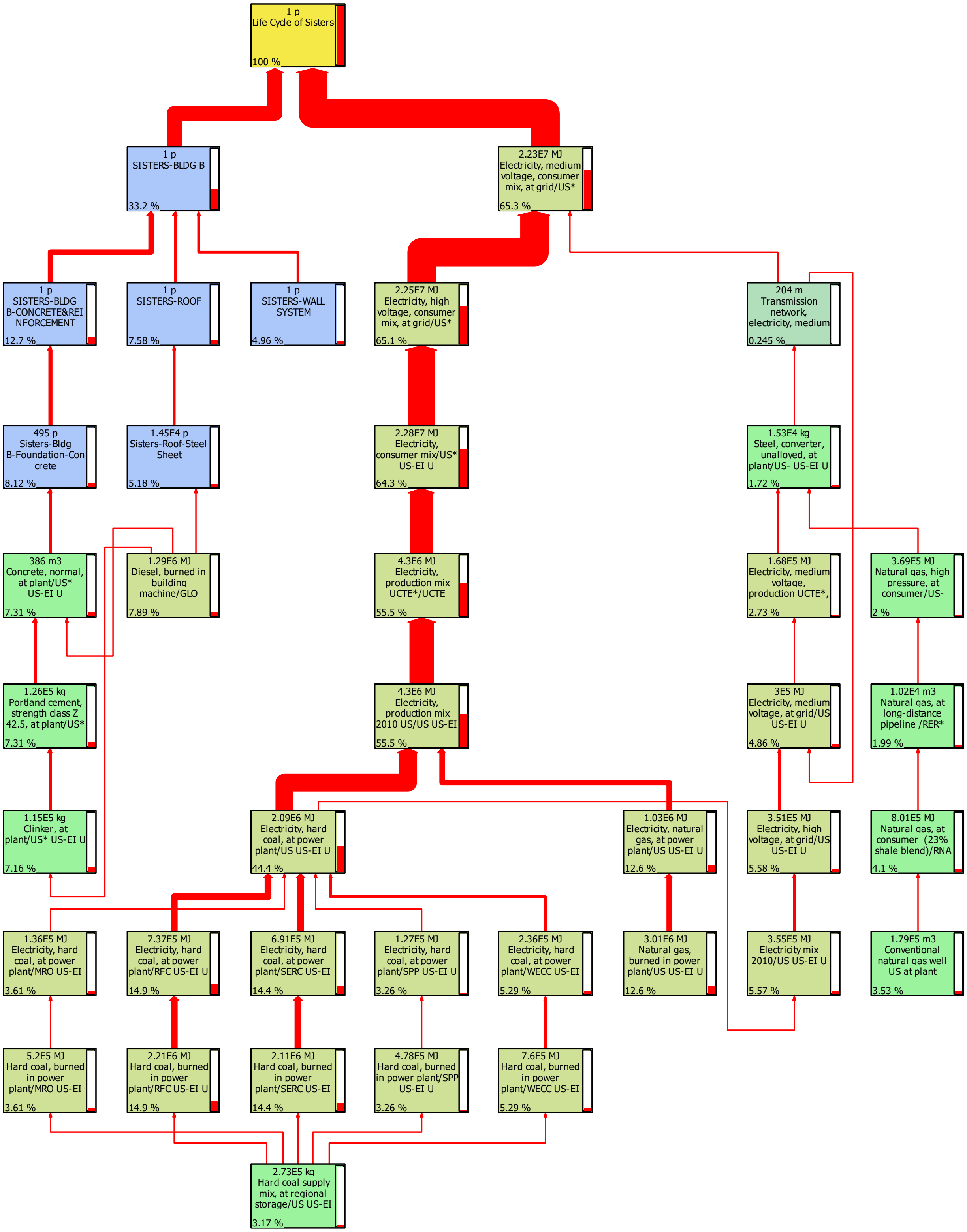


Figure 4.11. Network of process contribution (>3%) in terms of global warming - Sisters

Several alternatives were considered for the Sisters building based on prior recommendations for construction practices. Specifically, the research team examined the use of double pane and triple pane windows, clay and asphalt shingles roofing materials, and cellulose fiber and 45% recyclable polystyrene foam insulation materials as alternatives for existing materials of those structures. In addition, the use of Portland calcareous cement instead of Portland cement was also studied for further investigation of cement options in addition to the one presented in the Albany case.

4.1.2.1 *Alternative 1 – Use of Double Pane and Triple Pane Windows*

The environmental impacts of the three types of windows for Sisters are presented in Figure 4.12. The original window type examined is the existing aluminum single pane windows. The total window area was used; and transportation was also included.

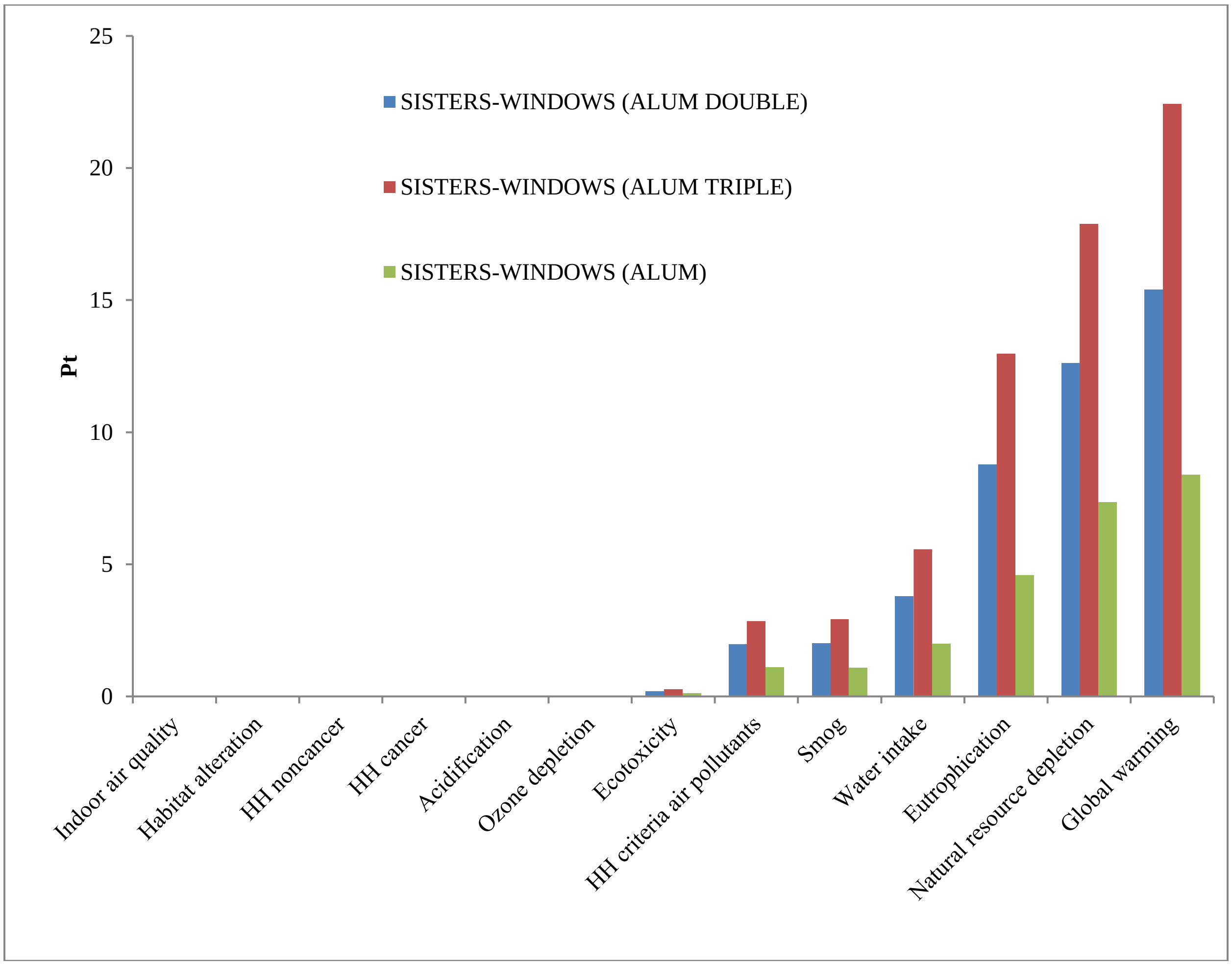


Figure 4.12. Use of double pane and triple pane windows comparison - Sisters building

For windows, Global Warming is the highest impact contributor among all impact categories, followed by Natural Resource Depletion, Eutrophication, Water Intake, Smog, Human Health Criteria Air Pollutants, and Eco-toxicity. The rate of increase in total impacts decreases for double and triple pane windows. Therefore, although double and triple pane windows generate additional impacts, further investigation due to the long-term energy saving during operational use is required to capture the true environmental impacts by switching from single to double or triple pane windows.

4.1.2.2 *Alternative 2 – Use of Clay and Asphalt Shingles Roofing Materials*

The impact assessment comparison for the three main roofing materials – steel sheets, clay tiles, and asphalt shingles, is presented in Figure 4.13. Steel sheets are the currently used roofing material in Sisters.

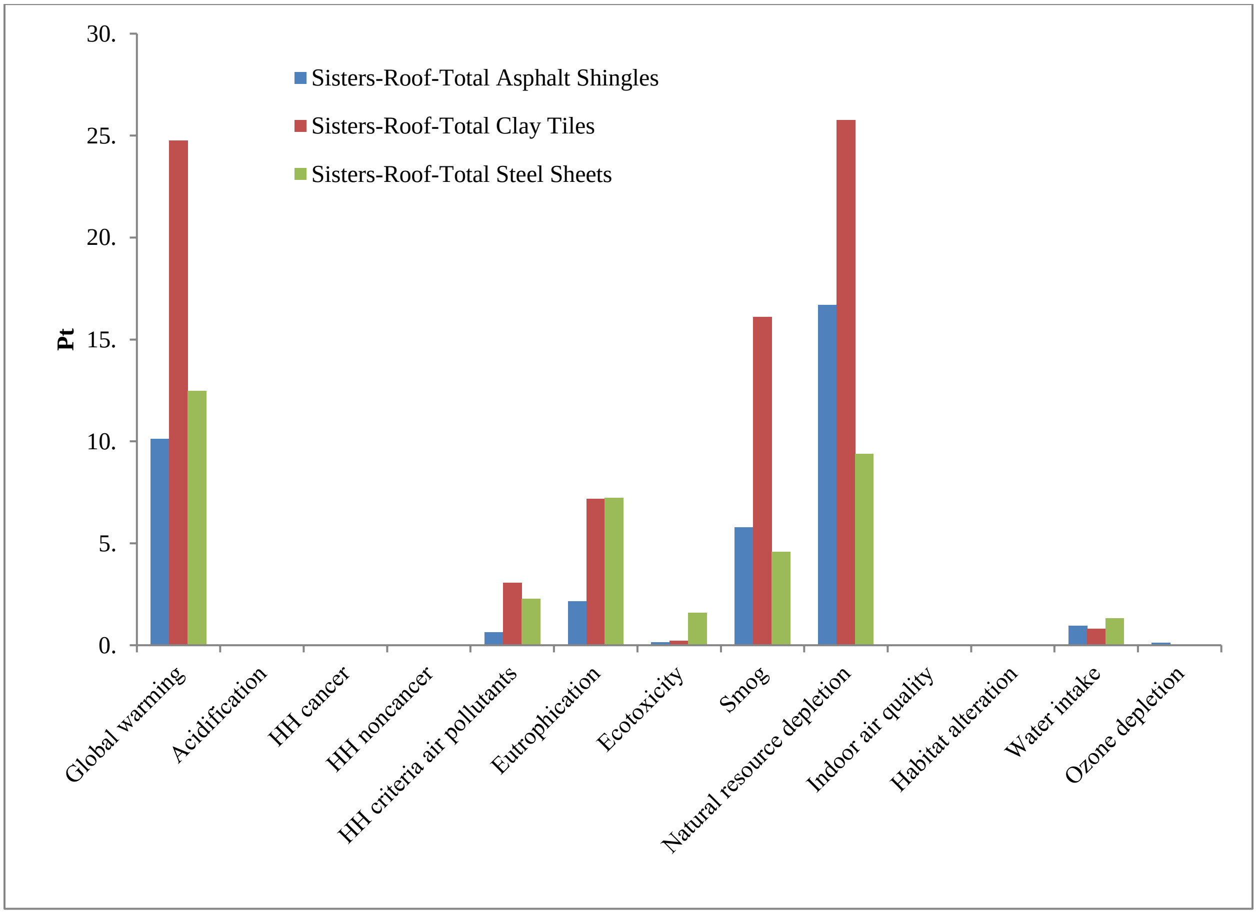


Figure 4.13. Impact assessment of alternative roofing materials - Sisters building

The three roof options present impacts in most impact categories, especially in terms of Global Warming, Human Health Criteria Air Pollutants, Eutrophication, Smog, Natural Resource Depletion, and Water Intake. Clay tiles produce significantly higher environmental impacts compared to the other two alternatives in terms of Global Warming, Smog, and Natural Resource Depletion. While asphalt shingles produce higher impacts than steel sheets in terms of Smog and Natural Resource Depletion, steel sheets yield higher impacts in all other main impact areas. In terms of total impacts, asphalt shingles perform only slightly better than steel sheets (36.6 versus 38.9 Pt), which may indicate further investigation on specific factors such as climate and transport distances for specific situations is required. Overall, clay tiles may be the least preferred choice for roofing materials, and asphalt shingles the least impactful in terms of total impacts.

The excess impacts produced by clay tiles may be due to the density of this material – 6 lb/ft^2 (Boise Cascade, 2016), which affects the installation process due to transportation on site and breakage (Peurifoy, 2008, p. 320). Further exploration of this roofing material reveals that diesel burned in building machine (heavy equipment used during construction of buildings) is the main process contributor to the total environmental impacts for Clay Tiles, as seen in Figure 4.14.

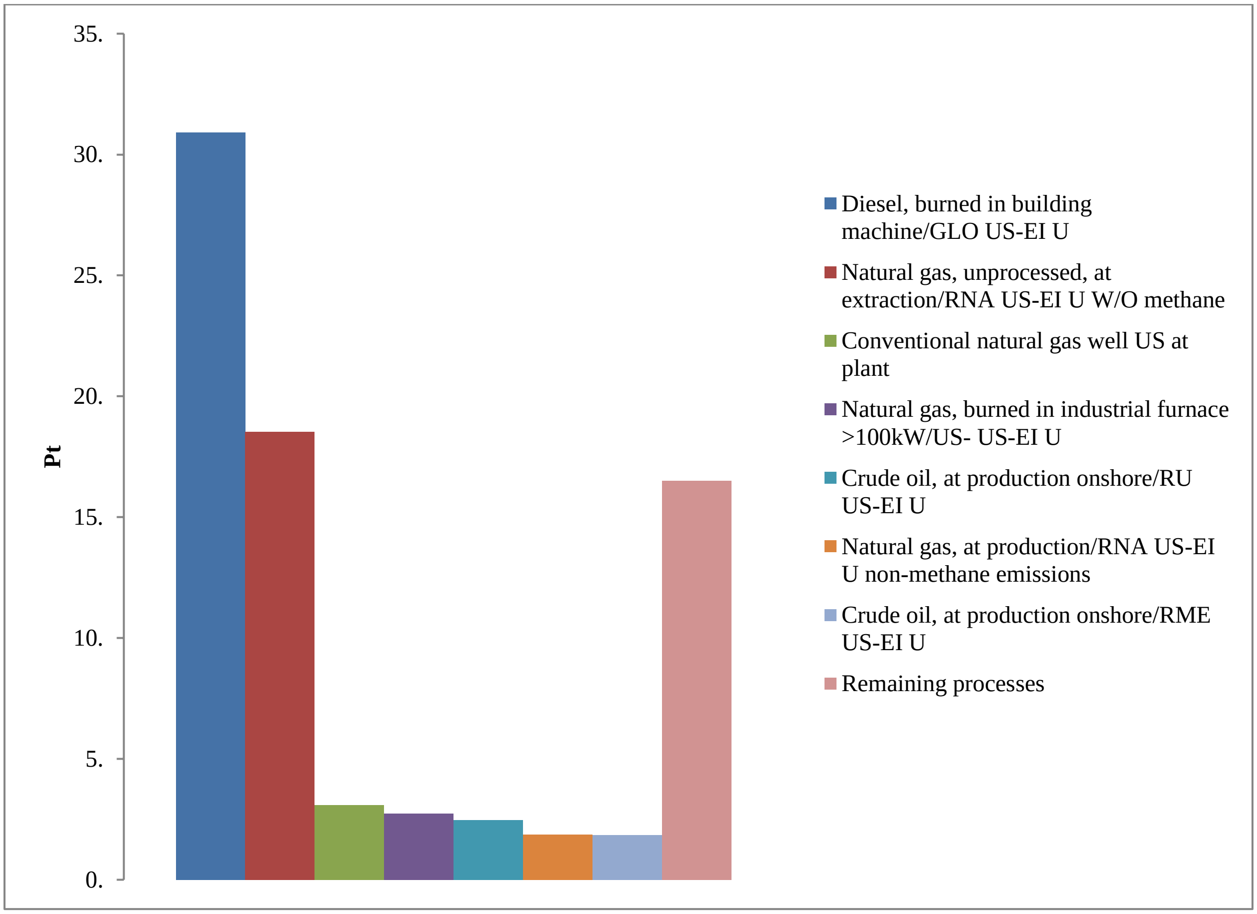


Figure 4.14. Total impacts per process (>2%) - clay tiles roof - Sisters building

Besides diesel used in heavy equipment at construction site as the highest process-contributor (Sharrard et al., 2007), natural gas used during material extraction also contributes significantly to the total impacts. Exploration of recyclable methods for clay tiles production may improve the total environmental performance of this roofing material.

4.1.2.3 *Alternative 3 – Use of Cellulose Fiber and 45% Recyclable Polystyrene Foam Insulation Materials in Wall System*

The comparison among the two alternatives and the original glass fiber for insulation material used within Sisters building's wall system are presented in Figure 4.15.

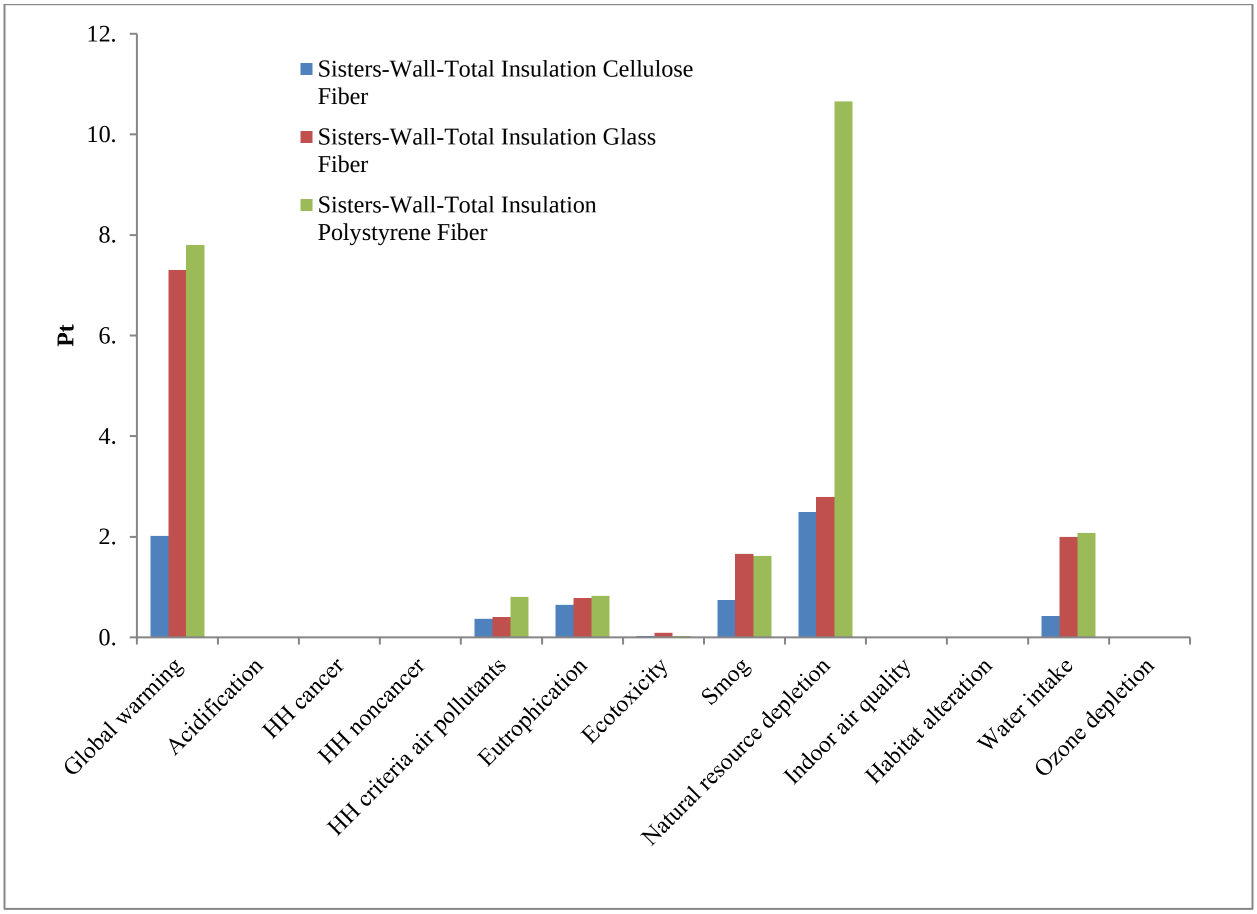


Figure 4.15. Impact assessment of insulation options - Sisters building

In terms of environmental impacts, the three insulation materials seem to produce impacts within Global Warming, Human Health Criteria Air Pollutants, Eutrophication, Smog, Natural Resource Depletion, and Water Intake impacts criteria. Cellulose fiber seems to produce the least environmental impacts among the three options. Cellulose fiber also performs notably better in terms of Global Warming, Smog, and Water Intake when compared to Glass Fiber and 45% Recyclable Polystyrene Fiber. However, 45% Recyclable Polystyrene produces the most impacts in all categories except Eco-toxicity and Smog, especially in terms of Natural Resource Depletion. Reduction in impacts in terms of Eco-toxicity and Smog is also minimal. Glass Fiber remains average between the other two insulation options, except in terms of Smog where it has the highest impact.

Based on Figure 4.15, cellulose fiber appears to be the most improved insulation material among the three options.

4.1.2.4 *Alternative 4 - Use of Portland Calcareous Cement*

The impact assessment of the use of Portland calcareous cement in Sisters Building versus the original Portland cement is presented in Figure 4.16.

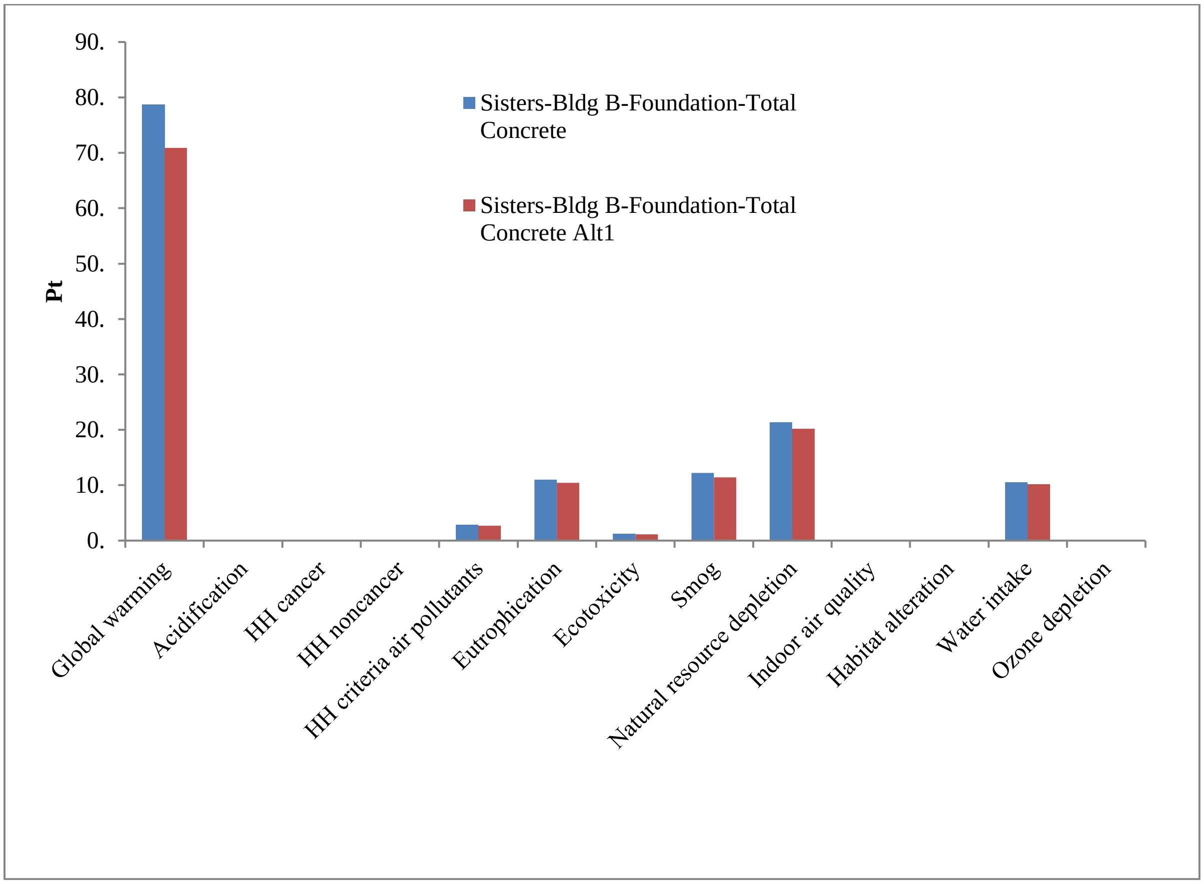


Figure 4.16. Impact assessment of the use of Portland calcareous cement - Sisters building

Similar to the case of concrete used in Albany building, the same main impact categories – Global Warming, Human Health Criteria Air Pollutants, Eutrophication, Eco-toxicity, Smog, Natural Resource Depletion, and Water Intake – for concrete are presented. Minor impacts reduction is observed in all of the above impact categories when the alternative cement is used, with Global Warming seen the most reduction. However, the reduction is not as much as reduction from the use of blast furnace slag cement concrete in the case of Albany, suggesting blast furnace slag cement concrete is still a preferable choice.

4.1.3 Uncertainty Analysis

Uncertainty analysis was performed on the life cycle impacts of Albany and Sisters buildings, as well as the comparisons of life cycle impacts and building structure impacts of Albany versus Sisters buildings, as presented in the following sub-sections. Monte Carlo analysis was used to calculate variation in the results based on distributions that were included in SimaPro's database.

4.1.3.1 *Uncertainty Analysis of Albany Building's Life Cycle Assessment*

The median and variation of each impact category for Albany's LCIA results can be visualized in Figure 4.17. Extreme outliers can also be identified from this figure.

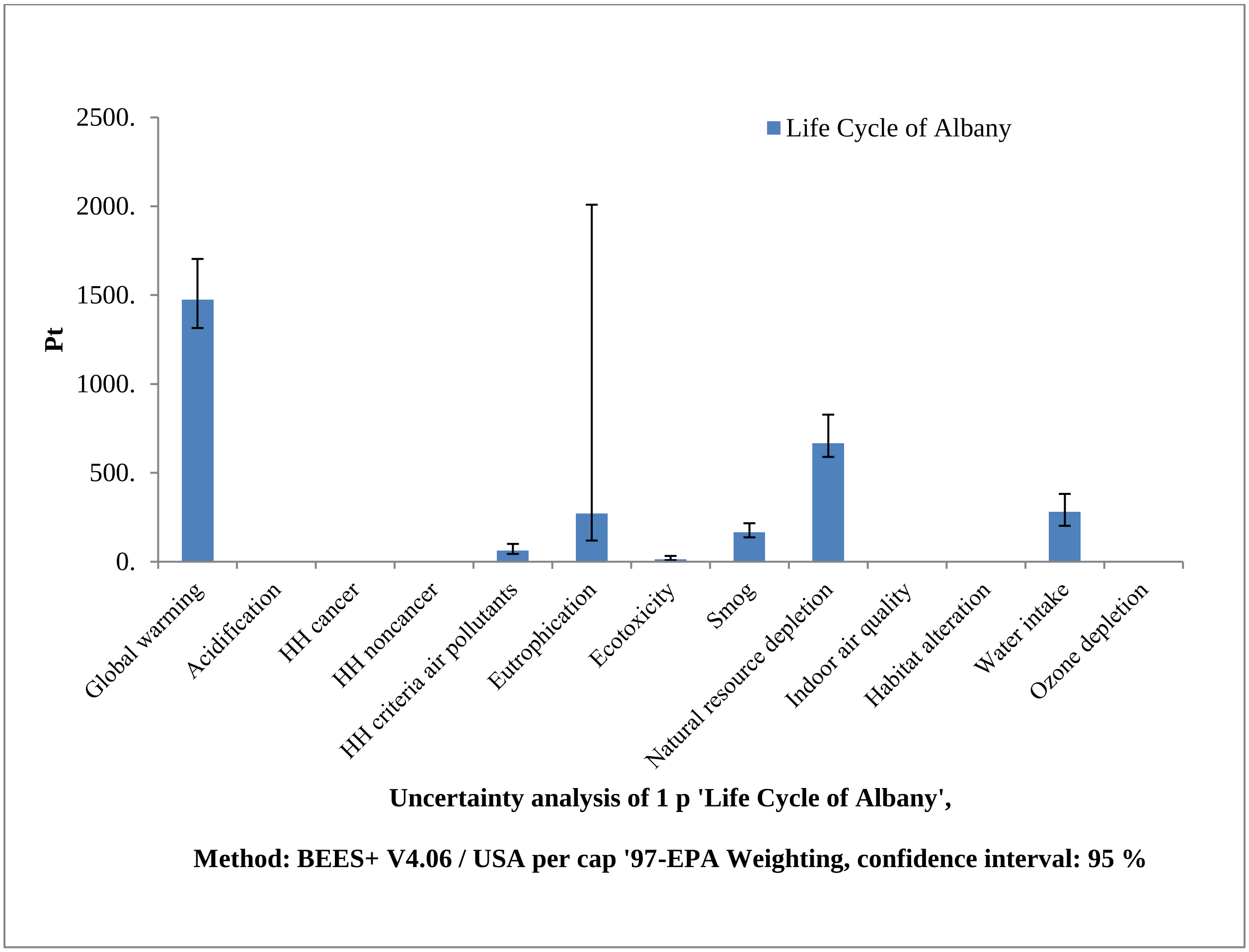


Figure 4.17. Uncertainty analysis - Albany building environmental impacts

The impact category with the highest measure of spread is Eutrophication, indicating high uncertainty in the assessment of this particular impact category. Global Warming, Natural Resource Depletion, and Water Intake seem to present both lower variation and closeness of median and mean values. This provides higher confidence in the assessment results for these impact categories. Human Health Criteria Air Pollutants and Smog also present narrow confidence intervals; however, the 97.5% values for both categories show significant deviation from the median values, which indicates possible presence of some outliers.

Details on common statistics – mean, median, standard deviation (SD), coefficient of covariance (CV), confidence interval (2.5% and 97.5%), and standard error mean (SEM) for LCIA results of Albany building can be found in Table 4.1.

Table 4.1. Life Cycle of Albany Building - Statistics

Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Acidification	Pt	0.36	0.35	0.08	21.27	0.25	0.55	0.00
Ecotoxicity	Pt	15.78	14.18	6.99	44.29	8.97	32.74	0.22
Eutrophication	Pt	443.01	271.65	734.77	165.86	119.29	2009.03	23.24
Global warming	Pt	1484.69	1476.51	96.35	6.49	1314.95	1703.62	3.05
Habitat alteration	Pt	0.00	0.00	0.00	127.52	0.00	0.00	0.00
HH cancer	Pt	0.76	0.67	0.34	44.57	0.45	1.58	0.01
HH criteria air pollutants	Pt	65.05	62.13	17.39	26.73	43.95	100.35	0.55
HH noncancer	Pt	0.54	0.48	0.29	54.42	0.28	1.11	0.01
Indoor air quality	Pt	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural resource depletion	Pt	676.73	667.45	72.94	10.78	589.87	827.66	2.31
Ozone depletion	Pt	0.93	0.92	0.07	7.53	0.83	1.10	0.00
Smog	Pt	169.23	165.61	26.55	15.69	137.22	216.46	0.84
Water intake	Pt	286.87	282.79	46.12	16.08	202.17	381.76	1.46
Confidence interval:	95							

4.1.3.2 *Uncertainty Analysis of Sisters Building's Life Cycle Assessment*

Similarly, visualization of the medians and variations for the impact categories resulting from the life cycle of the Sisters building is presented in Figure 4.18.

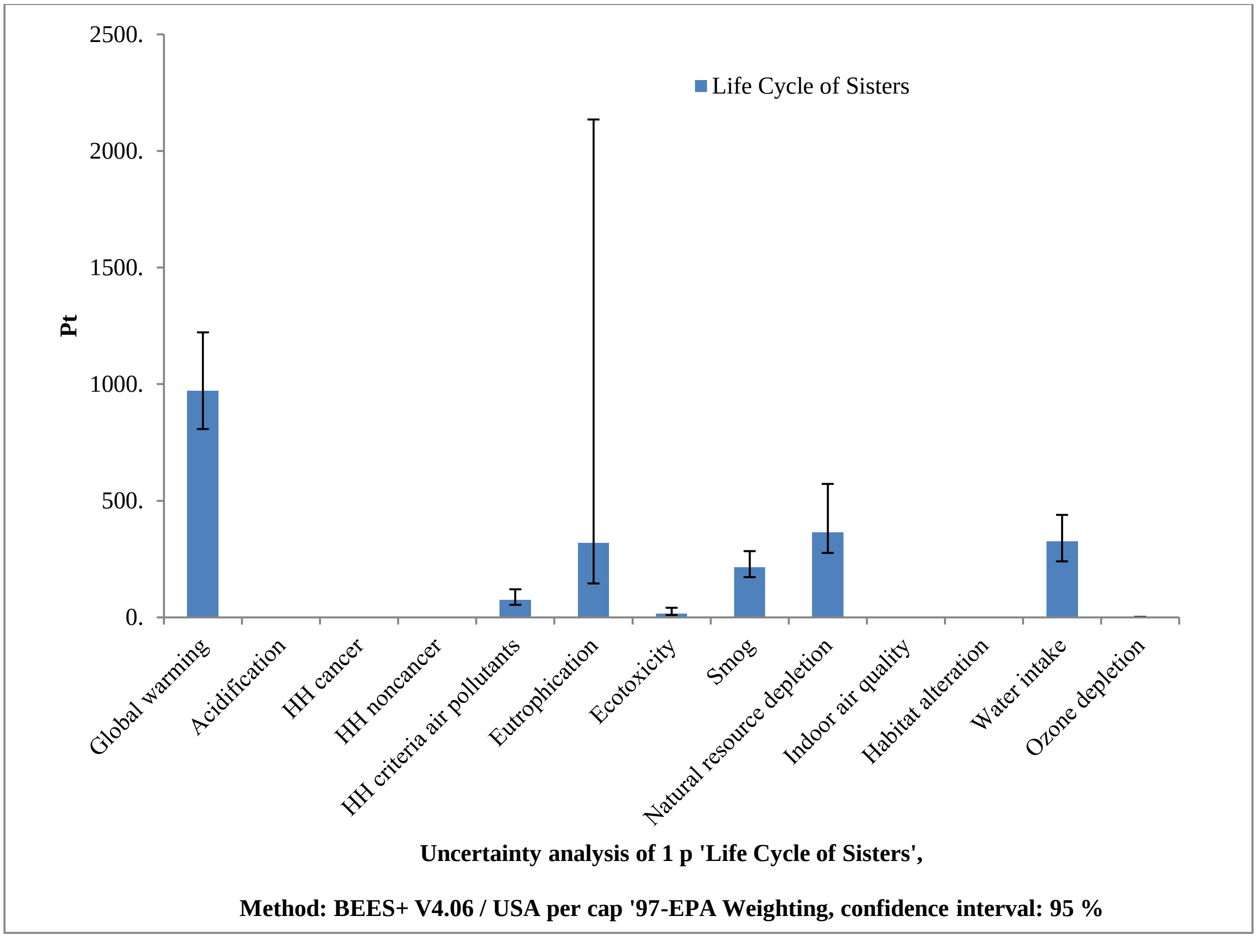


Figure 4.18. Uncertainty analysis - Sisters building environmental impact

Eutrophication also presents the highest variation among all impact categories, which indicates high uncertainty in the assessment result regarding this impact category. Natural Resource Depletion also presents a high variation value and some deviation from centrality. Global Warming and Water Intake present both relatively low measures of spread and distance between the mean and median values. Human Health Criteria Air Pollutants and Smog, although have relatively low variation, show possible presence of outliers; however, these outliers are not extreme as seen in the case of Eutrophication. Common statistics for the LCIA results of Sisters building can be found in Table 4.2.

Table 4.2. Statistics - Life Cycle of Sisters Building

Impact category	Unit	Mean	Median	SD	CV	2.50%	97.50%	SEM
Acidification	Pt	0.43	0.42	0.10	22.03	0.30	0.68	0.00
Eco-toxicity	Pt	19.17	16.92	9.08	47.38	10.33	41.33	0.29
Eutrophication	Pt	522.73	319.73	714.68	136.72	145.63	2134.89	22.60
Global warming	Pt	981.95	972.24	108.86	11.09	807.65	1222.21	3.44
Habitat alteration	Pt	0.00	0.00	0.00	122.25	0.00	0.00	0.00
HH cancer	Pt	0.87	0.79	0.39	44.81	0.53	1.64	0.01
HH criteria air pollutants	Pt	76.85	73.66	17.67	22.99	54.01	120.48	0.56
HH noncancer	Pt	0.64	0.58	0.29	45.69	0.36	1.36	0.01
Indoor air quality	Pt	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Natural resource depletion	Pt	378.99	364.91	80.49	21.24	276.58	572.42	2.55
Ozone depletion	Pt	1.94	1.92	0.14	6.98	1.75	2.27	0.00
Smog	Pt	219.11	216.02	30.24	13.80	172.53	284.27	0.96
Water intake	Pt	328.97	325.85	51.96	15.80	240.35	439.59	1.64
Confidence interval:	95							

4.1.3.3 *Uncertainty Analysis of Life Cycle Assessment Comparison*

The higher uncertainty in life cycle impacts for the Albany facility can be visualized in Figure 4.19.

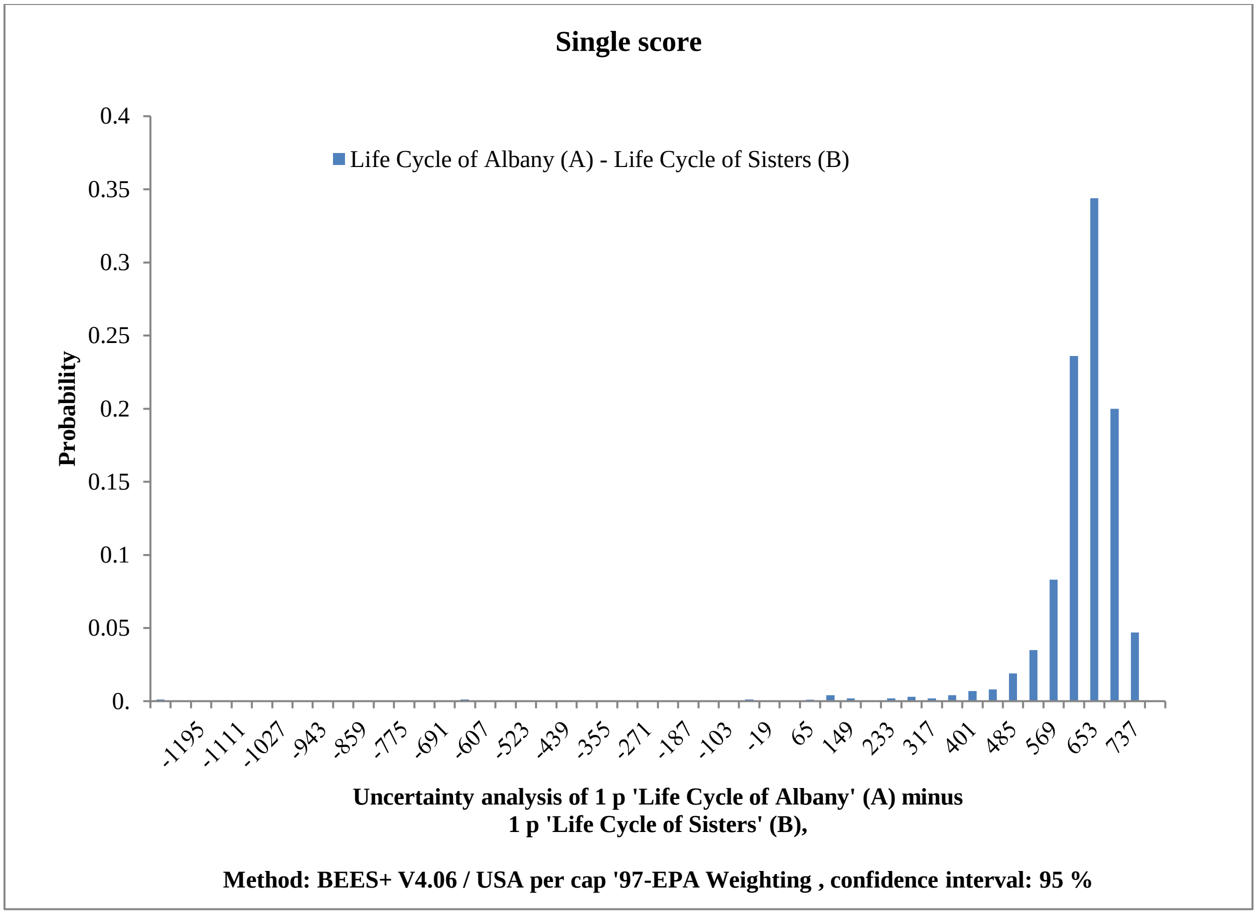


Figure 4.19. Probability of differences in life cycle impacts of Albany vs. Sisters buildings

Figure 4.19 provides strong confidence that the life cycle impact (measured by single score (Pt)) of the Albany facility (A) exceeds that of the Sisters facility (B), as 100% of the differences have positive values. The spread of the differences also provides high confidence for the conclusion of the comparison, with 90% of the data that measures the difference falls between 569 and 737 Pt. Further, exploring the uncertainty of this comparison by each impact category provides additional confidence in the comparison results, as the likelihoods associated with the differences in all impact categories are approximately 100%, as seen in Figure 4.20.

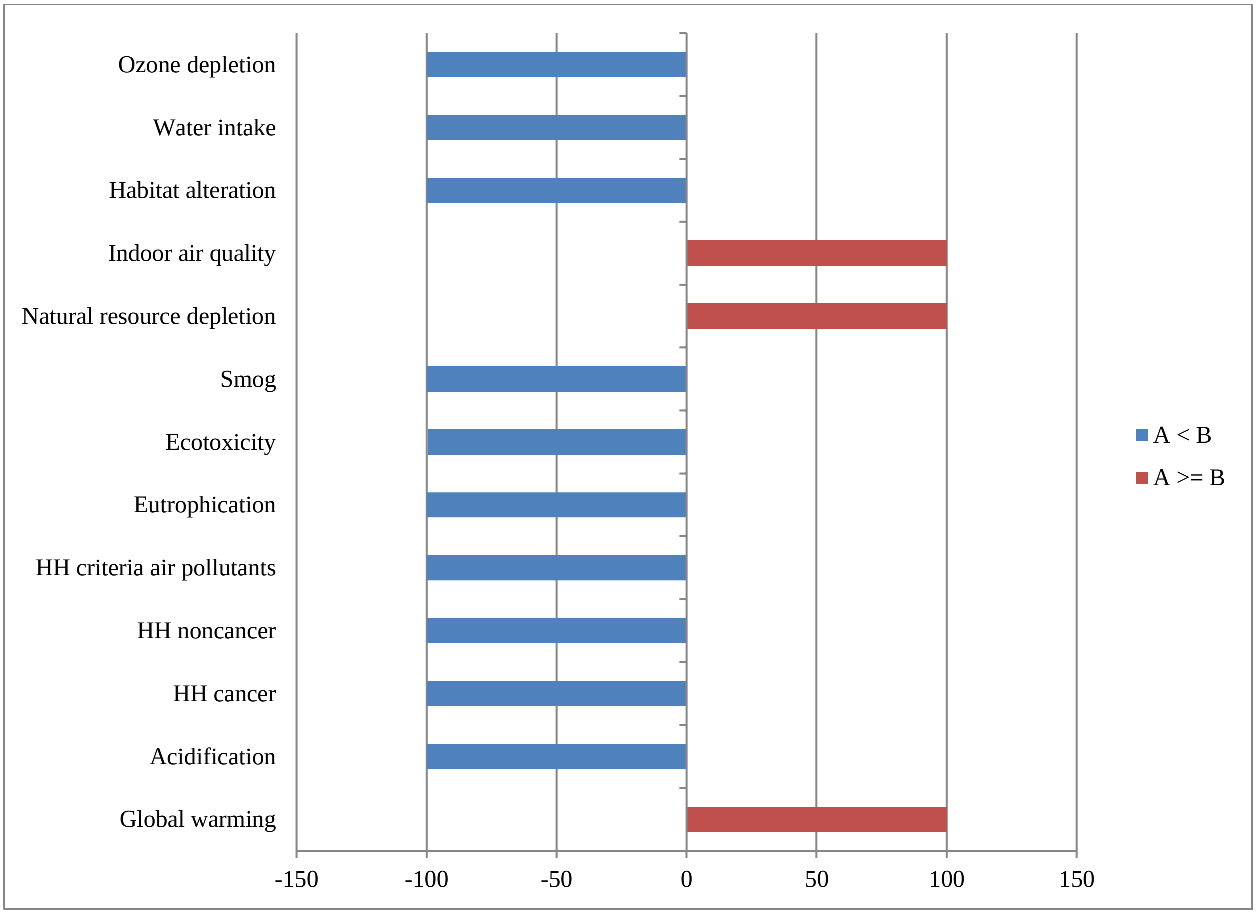


Figure 4.20. Probability of differences in impacts per impact category

The figure also provides additional insights on which impact categories are higher in the case of the Albany or Sisters buildings. Global Warming, Natural Resource Depletion, and Indoor Air Quality appear to be the main drivers for the Albany building exceeding the Sisters building in overall impacts score.

4.1.3.4 *Uncertainty Analysis of Structural Comparison*

The prior conclusion on the higher impact score of the Sisters building structure can be assessed by the visualization in Figure 4.21. Probability of differences in impacts of structure

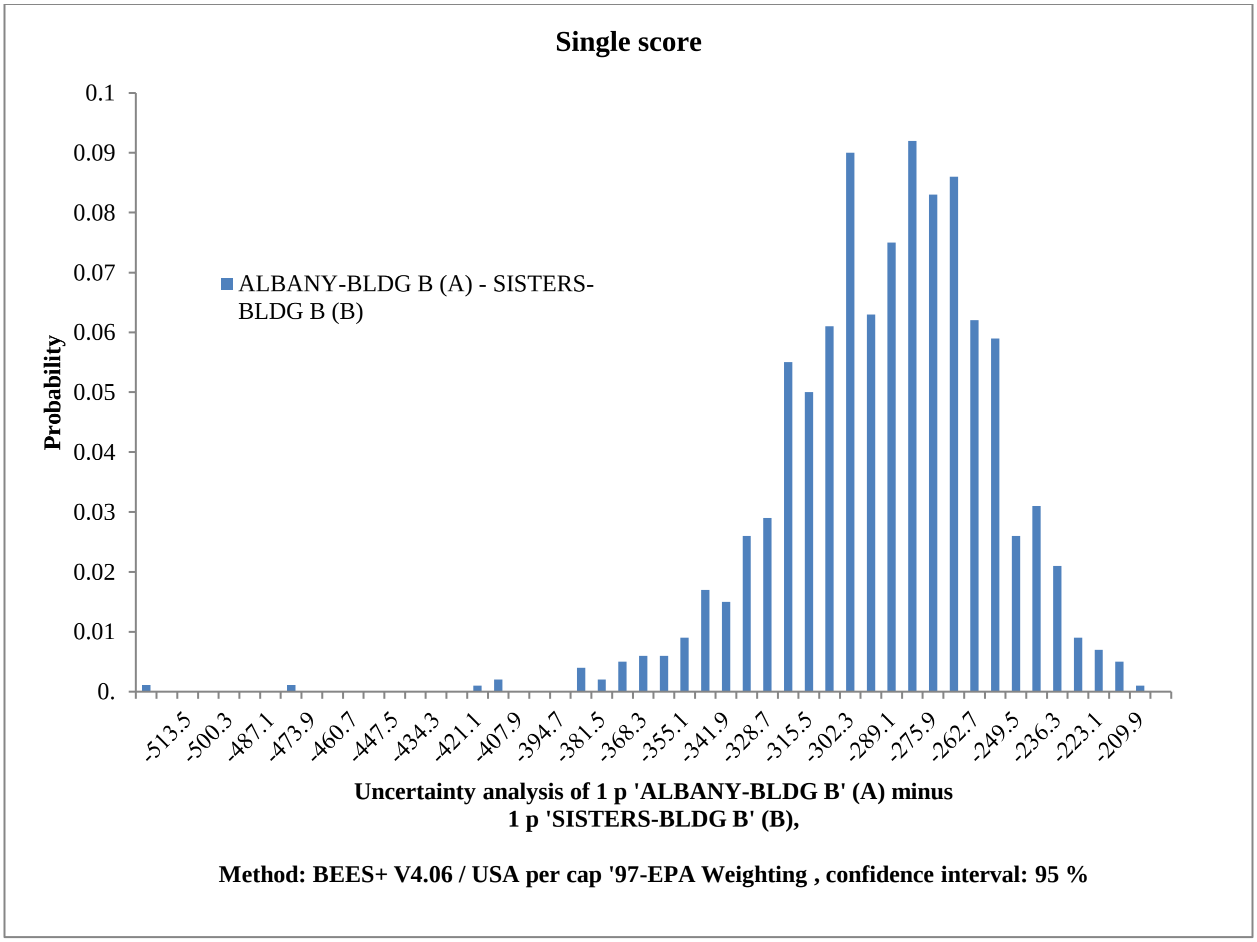


Figure 4.21. Probability of differences in impacts of structure components

Subtracting the single score impact of the Albany building structure from that of the Sisters Building structure results in 100% negative values. However, the spread of the probabilities associated with these negative values is high compared to the comparison of life cycle impacts; indicating some difficulty locating the difference value point with high certainty. The difference value point with the highest probability (9%) is -282.5 Pt.

Uncertainty of the difference in impacts associated with building structure by the impact categories is presented in Figure 4.22.

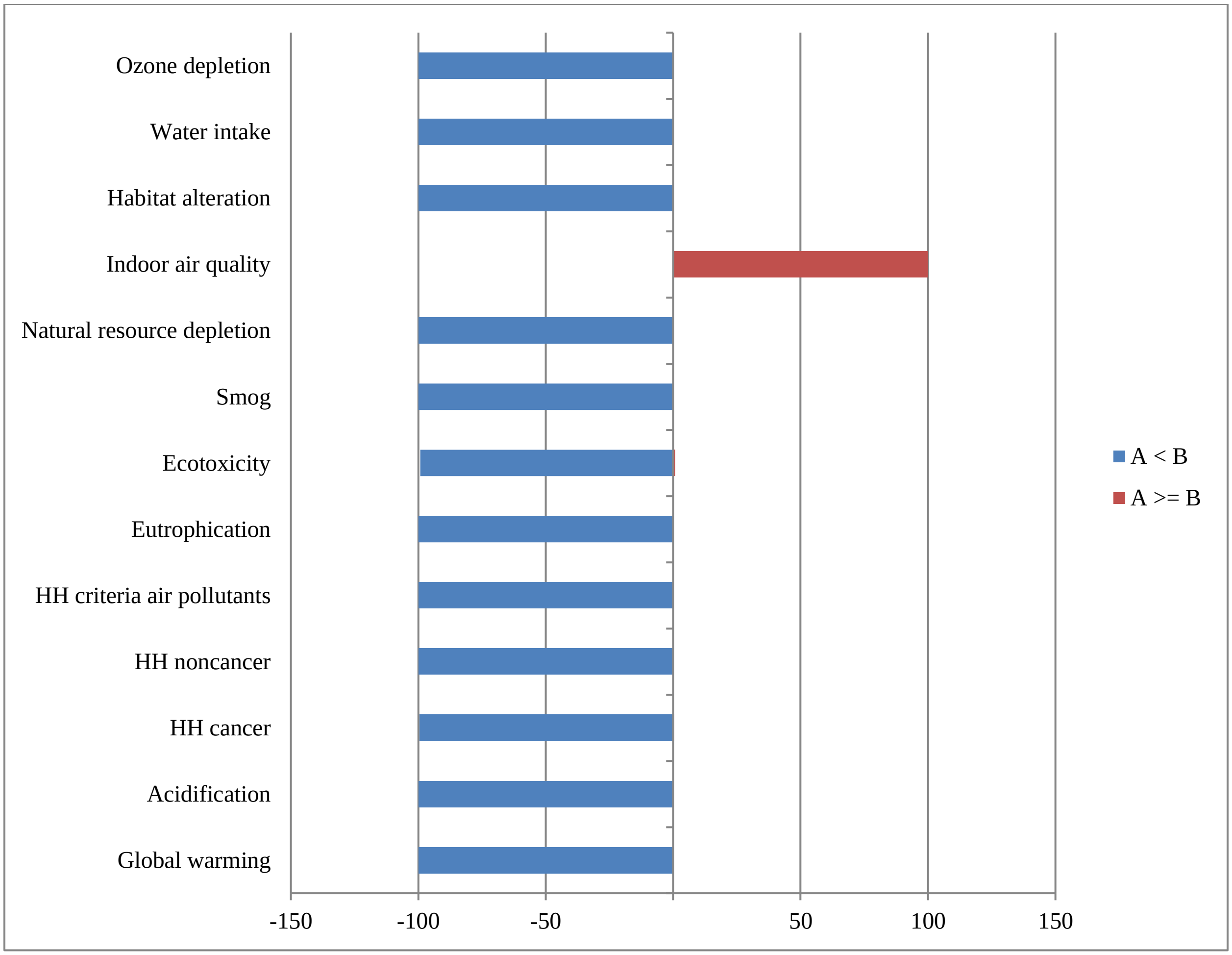


Figure 4.22. Probability of differences in impacts of building structure by impact categories

The majority of the impacts associated with Albany building's structural components have display high certainty to be less than that of Sisters building structure. However, indoor air quality of Albany building structure, although not among the main impact categories associated with either buildings, presents high certainty to be higher than that of Sisters building structure.

4.2 LIFE CYCLE COST ANALYSIS

The initial investment for each facility was phased over approximately three years. The reported cost for each year during the phase-in period is in current dollars, i.e., inclusive of escalation rate and inflation. These costs were brought forward to 2016 current dollars, as presented in Table 4.3, which provided input values to be used in the BLCC-5 life cycle costing software tool.

Table 4.3. Calculation of LCCA Inputs for Investments

Facility	Year	Actual Cost	Note	Nominal Rate*	FV16*
Albany	1993	$416,342	Descriptions from ODOT cost spreadsheets: Albany MT Design NEW, NEW Albany MS Prop, New Albany MS Design	3.5%	$918,499
	1994	$64,659		3.5%	$137,821
	1995	$1,052,610		3.5%	$2,167,779
	1996	$8,387		3.5%	$16,689
	TOTAL	$1,541,999		TOTAL (BLCC-5 input)	$3,240,788
Sisters	2010	$0	Assumed negligible	2.4%	$0
	2011	$241,575	Cost spreadsheet obtained from Mr. Pat Creedican	2.4%	$271,989
	2012	$2,732,455	Remaining after other costs	2.4%	$3,004,366
	2013	$117,407	Retainage value obtained from Mr. Pat Creedican	2.0%	$124,593
	TOTAL	$3,091,437	Cost provided by Mr. Luis Umana via email	TOTAL (BLCC-5 input)	$3,400,949

* Nominal rate to convert to current 2016 dollars (Future Value in 2016, FV16).

BLCC-5 calculates the total investment costs, unadjusted for escalation, by adjusting the value of each year's cost by the agency's contractual rate, also known as the Cost Adjustment Factor. For example, assuming that the escalation rate is 3.5% during the construction period and the Cost Adjustment Factor is 2%, the 1994 cost entry for investments into the Albany facility would be adjusted to the base year (1993) as seen in Eq. 4-1:

$$\boldsymbol{PV_{Alb}} = \frac{\$\mathbf{137,821}}{(\mathbf{1}+\mathbf{3.5}\%)^{\mathbf{1}}} \times (\mathbf{1}+\mathbf{2}\%)^{\mathbf{1}} = \$\mathbf{127,753}$$

(4-1)

Consequently, the total life cycle cost for each facility would be calculated as the sum of each adjusted investment cost entry determined using Eq. 4-1.

Using similar approach, BLCC-5 calculates annually recurring, non-annually recurring, renovation, and replacement costs to estimate the total life cycle costs, as seen in Eq. 4-1. The life cycle costs determined using this approach for the Albany and Sisters facilities are $3,871,596 and $3,927,201, respectively. The detailed LCCA report produced by BLCC-5 can be found in Appendix H. The summary of the main cost components are presented in Table 4.4 and Figure 4.23.

Table 4.4. Life Cycle Cost Summary for Main Cost Components

	Albany	Sisters
Initial Investment	$3,175,083	$3,280,897
Annually Recurring	$186,496	$345,914
Replacement	$38,811	$0
Energy Consumption	$387,129	$229,958
Energy Demand	$67,284	$39,146
Non-Annually Recurring	$16,793	$31,936
Total LCC	$3,871,596	$3,927,201

The life cycle costs of the initial investments are quite similar between the two buildings, reflected in 2016 dollars. One significant renovation was done at the Albany maintenance facility and is reflected as the $38,811 replacement cost. The overall energy consumption cost is lower for the Sisters facility by over $150,000, highlighting the value of the energy-saving ground source heat pump and combined solar panels (to meet SEED requirements), compared to the traditional systems used at the Albany Facility for electrical energy and facility heating. The Sisters facility does have higher annually recurring costs (likely owing to the characteristics of winter operations, or its larger service area, and more remote service region). However, the initial modifications needed at a newer facility that may taper off over a 50-year lifespan are not reflected in the available data.

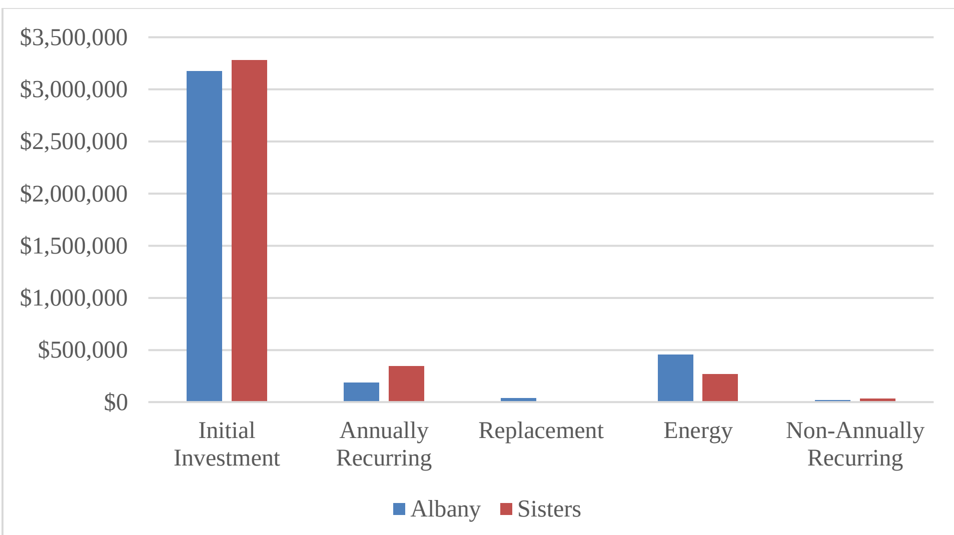


Figure 4.23. Life cycle cost for main components

The cost driver for both facilities is their initial investment, with the Sisters facility's initial investment being slightly higher (3%) than the Albany facility's initial investment. Annually and non-annually recurring costs for the Sisters facility are also higher than those for the Albany facility. However, replacement costs and energy related costs for Sisters are lower than those costs for Albany.

4.2.1 Annually Recurring Cost Breakdown

Figure 4.24 and Figure 4.25 display the breakdown of the annually recurring costs for the Albany and Sisters facilities, respectively.

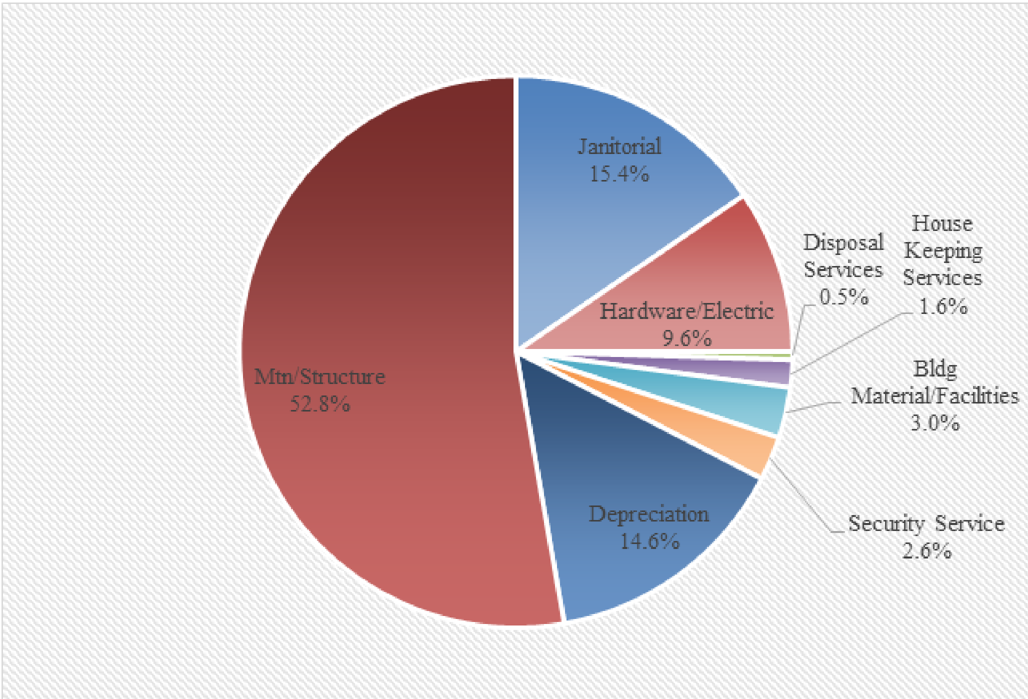


Figure 4.24. Annually recurring cost breakdown for Albany

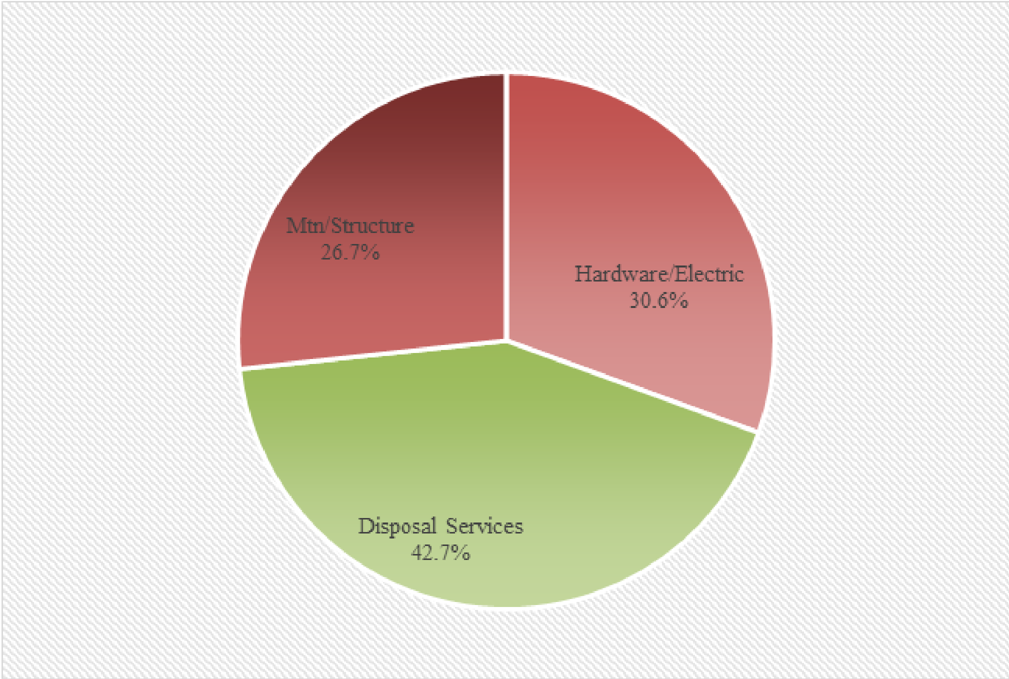


Figure 4.25. Annually recurring cost breakdown for Sisters

Significant savings for the Albany building can be observed by eliminating the costs of janitorial services, housekeeping services, and security services, as seen in the case of the Sisters building.

The Sisters facility has not established the variety of cost categories as in the case of Albany. The high disposal services and hardware/electric costs for Sisters might be due to new purchases of equipment and services to meet the facility's requirements, and the location of the facility. These costs require further monitoring to derive a plausible explanation. Site selection can have a significant impact on the life cycle cost, and so geographical consideration of future buildings would benefit from further investigation of these costs.

4.2.2 Non-annually Recurring Cost Breakdown

Figure 4.26 and Figure 4.27 display the non-annually recurring cost breakdown for each facility. Savings for Albany can be observed by reducing costs of structural repairs and HVAC repairs by selecting more durable and reliable materials and equipment.

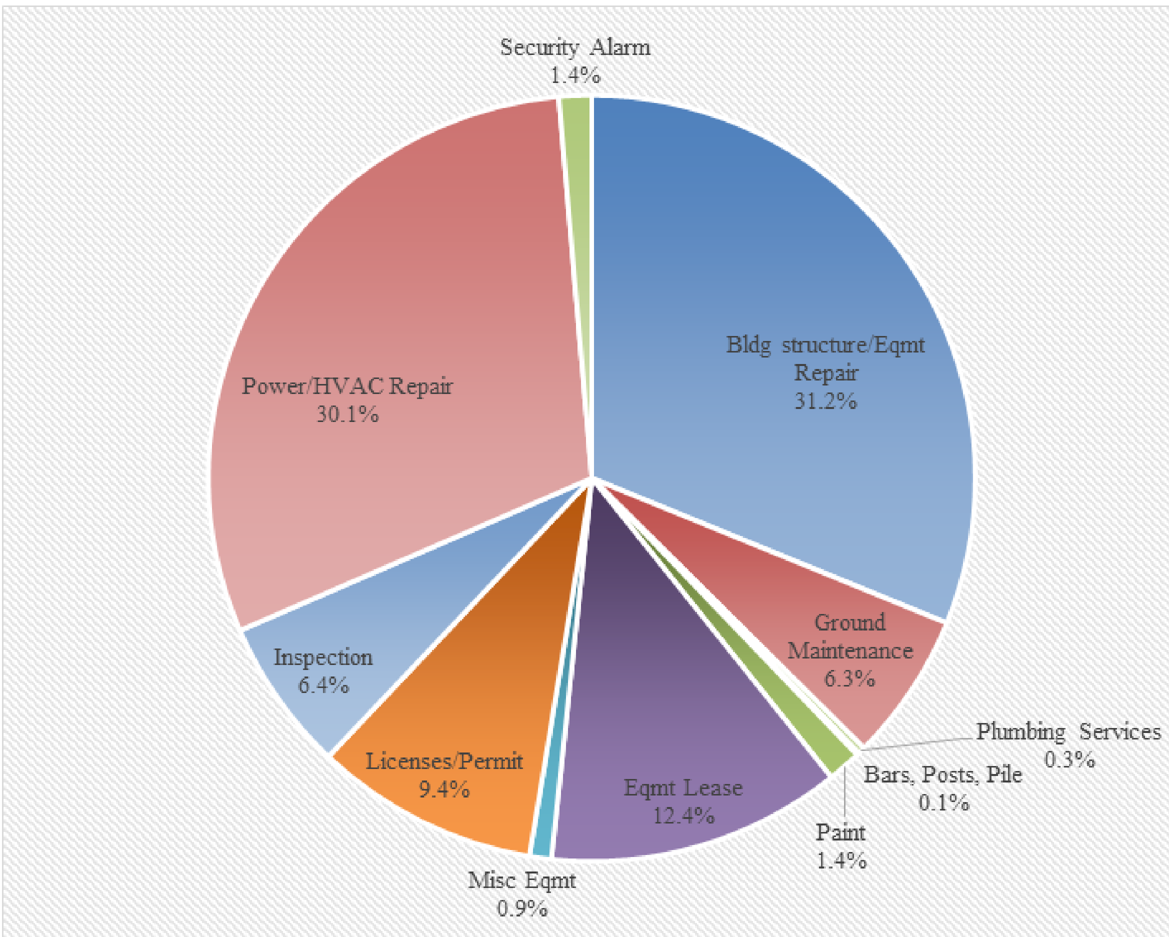


Figure 4.26. Non-annually recurring cost breakdown for Albany

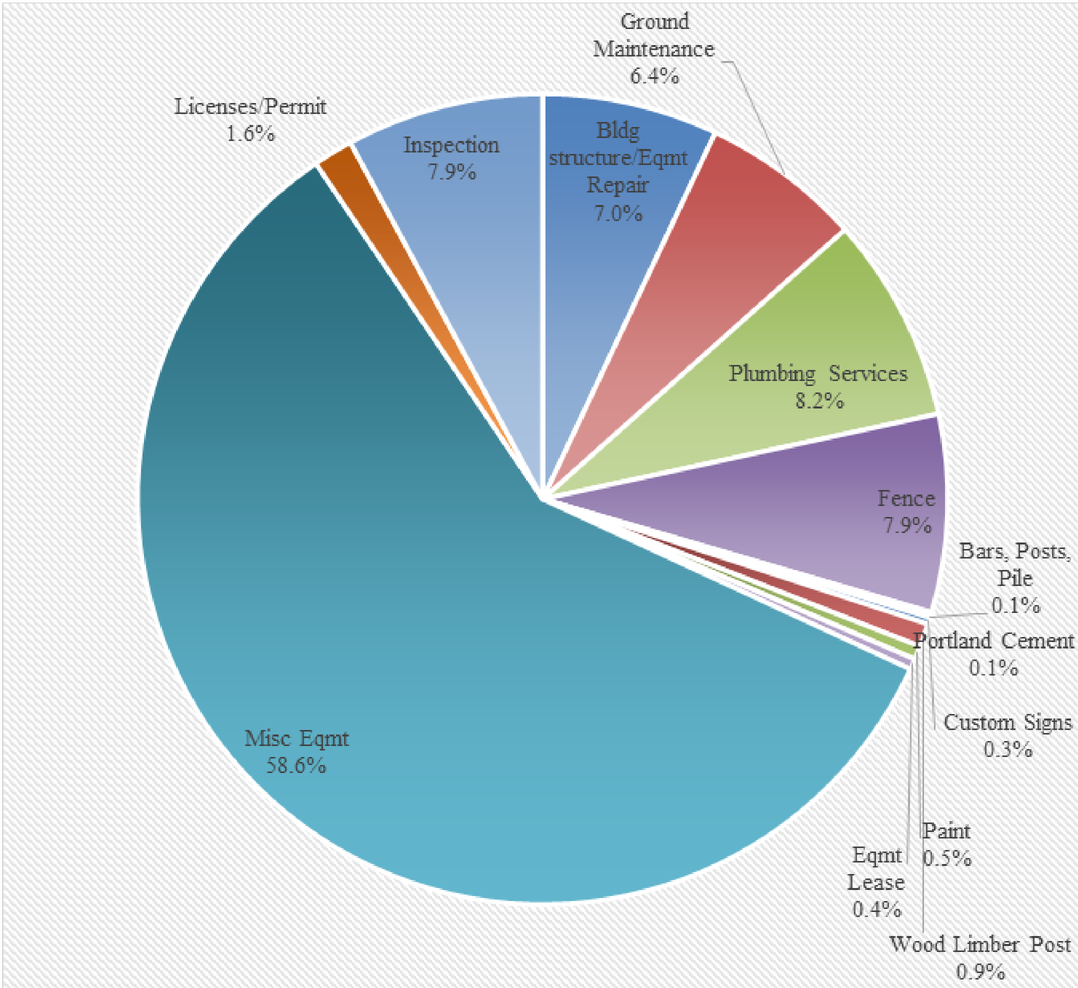


Figure 4.27. Non-annually recurring cost breakdown for Sisters

Miscellaneous equipment costs are the highest component of non-annually recurring costs for the Sisters facility ($19,420 in 2016 dollars), which may be due to obtaining of a variety of equipment for the operational requirements of the new building.

4.3 SUMMARY

4.3.1 Summary of Life Cycle Assessment Results

LCA was performed on ODOT's Albany and Sisters maintenance facilities using BEES methodology and SimaPro as the LCA database and calculation software. Impact scores for each facility were also normalized by their respective areas for comparison. Overall, the life cycle Global Warming score (after normalization) of the Albany facility (0.155 kPt/ft^2) is higher than that of the Sisters facility (0.0945 kPt/ft^2).

The total impact score for materials and usage of the main energy system at each facility also resembles the trend in total life cycle impact scores. The main driver for the high impact score at Albany facility is due to natural gas used for heating. Different natural gas burning process to produce electricity is the main impact driver for the Sisters facility. By replacing the current energy system at the Albany building with the solar-geothermal system being used at the Sisters building, the total impact score drops from 3.2 kPt to 2.3 kPt.

Structure-wise, the Sisters building has a higher normalized total impact score (0.0313 Pt/ft^2) compared to that of the Albany facility (0.0233 kPt/ft^2). This indicates that energy system choice and energy usage for operations throughout the life cycle of the building (50 years) determine the comparison outcome. Roofing material (steel sheets) and concrete (Portland cement) contribute the most impacts in terms of materials in both buildings, while diesel used in heavy equipment during construction contributes the most impacts during construction phase.

Among the 13 impact categories included in BEES assessment methodology, Global Warming, Human Health Criteria Air Pollutants, Eutrophication, Ecotoxicity, Smog, Natural Resource Depletion, and Water Intake appear to be the main impacts caused by buildings of the Albany and Sisters facilities' type. Global Warming contributes the highest points to the total scores for both buildings.

Alternative materials for high impact materials – concrete, roofing material, insulation – were analyzed to examine their potentials for reducing impacts. Double and triple pane windows were also investigated for analysis of energy efficient design options in the future. In the case of concrete, the use of blast furnace slag cement produces the lowest total impacts when compare to using Portland cement and Portland calcareous cement; and Portland cement produces the highest impact score. Cellulose fiber used for wall insulation produces the lowest impact compared to glass fiber and polystyrene insulation. Asphalt shingles and steel sheets incur similar level of impacts, with asphalt shingles performing slightly better than steel sheets and clay producing the highest impacts in terms of roofing materials.

Impacts associated with transportation between the main phases of the life cycle and waste disposal at the end of life were negligible when compared to impacts from materials and energy used.

Uncertainty analysis was performed on the LCA of each facility and the comparative impact analysis of their life cycles and structures. Eutrophication presents the most uncertainty due to high variation in the data for both facilities, while conclusions on other impact categories present higher certainty. Comparison of impacts from life cycles and structures of both buildings also presents high certainty, with 100% positive values when subtracting life cycle impact score of Sisters facility from that of Albany, and 100% negative values when subtracting impact score of Sisters building structure from that of Albany.

4.3.2 Summary of Life Cycle Cost Analysis Results

The life cycle costs of the Albany and Sisters facilities were calculated as $3,871,596 and $3,927,201, respectively. This is equivalent to an average annual cost over a presumed 50-year life span of $161,070/year for the Albany facility and $163,384/year for the Sisters facility. The cost driver for both facilities is their initial investment, with Sisters facility's initial investment being 3% higher than for the Albany facility. Annually recurring costs and non-annually recurring costs for Sisters are also higher than those for Albany. However, replacement cost and energy related costs for Sisters are lower than those costs for Albany throughout the 50-year life span.

In terms of annually recurring costs, costs associated with maintenance/structure, hardware/ electrics, and disposal services are the main drivers for both facilities. Janitorial and depreciation costs are the main cost drivers associated with only the Albany facility. Albany also appears to have more annual cost categories, indicating more reliable cost prediction for different cost drivers. The low number of cost categories and their associated values for Sisters might be biased due to the short time since the facility was constructed, resulting in less available data. Savings for Albany can be obtained by reducing janitorial costs as seen in the case of the Sisters facility. The high disposal service cost for the Sisters facility might be due to its rural location. Thus, alternatives to waste disposal is a factor to be considered when planning future maintenance facilities.

In terms of non-annually recurring costs, building structure/equipment and HVAC repair are the main cost drivers for the Albany facility, while miscellaneous equipment cost is the major cost driver for the Sisters facility. Savings for Albany can be observed by reducing costs of structural repairs and HVAC repairs by selecting more durable and reliable materials and equipment. The fact that it is a new facility may explain the overall cost pattern at the Sisters facility. More details are needed to determine the cause of one-time high miscellaneous costs at the Sisters facility.

4.4 LIMITATIONS

There are several limitations related to this study. First, establishing the study's system boundaries presents the temporal and spatial limitations in order to generalize the results to all of ODOT's maintenance facilities. The 50-year life assumption might be an underestimate; as most of ODOT's maintenance facilities have longer life cycles; which results in additional renovation costs and activities. For the Life Cycle Assessments of both buildings, only the main buildings (building B at each location) were included. However, since the unit presented was normalized by the area of the buildings, the results give the "worst-case" scenario as the main buildings contain a lot more materials than building A at each location. However, some factors need to be considered in terms of generalization to other maintenance facilities, as the physical areas and structures of Building B at both facilities might vary depending on the locations, as well as the specific operations of other maintenance facilities.

Second, data collection and analysis also present some challenges. In terms of availability of data, the research team received substantial assistance from ODOT employees to help in collecting data and documents related to both facilities. However, challenges unique to each facility were met. In the case of the Albany facility, the building's blueprint was available only in scanned copies with hand-written corrections; which required quantity take-off to be performed manually and certain assumptions regarding measurements to be made. This likely affected the accuracy of the dimensional measurements of the structures. In the case of the Sisters facility, due to the building having only been in operations for four years at the time of the study, cost patterns were not yet established with high certainty; therefore, the research team made assumptions using the cost patterns at Albany facility. Both facilities were assumed to have similar maintenance related operations. Limitations of data availability for both buildings also include specific details of actual products and materials used, locations of suppliers (local or non-local), types of transportation vehicles, and actual duration for each task at the construction site. Assumptions were made using (1) commonly used products or parts that can be found online, (2) 30-mile local-only transport distance from suppliers using 32-ton lorry, and (3) estimated duration for main construction tasks (Peurifoy, 2008). Although the research team is confident that the variability of the data from the actual measurements is negligible regarding the above assumptions, further analysis can be performed once more data become available to gain more confidence in the study's results.

In terms of analyses performed on costs and environmental impacts of both buildings, some methods chosen also present some limitations. In the case of LCA, some materials were only available for assessment using the Economic Input/Output method on SimaPro, which models impacts based on cost and other economic models (Carnegie Mellon University, 2008) and therefore increases uncertainty by introducing additional proxy variables. However, only a few of the material inputs were analyzed by this method. In terms of modeling waste scenario, choosing the EPA's model for US scenario might not be accurate depending on the specific regions due to different standards and regulations, as well as specific waste materials of buildings. This also affects the modeling of the recycling phase at the end of life of the products. Regarding modeling recycling process during raw material acquisition and production phases, using existing models available in SimaPro might not accurately depict real-life recycling of those materials in the US. In the case of LCCA, assuming annually recurring cost for the maintenance/structure cost category by aggregating all annual costs in this category ranging from $0 to $1000 as $1000 for both facilities most likely will result in over-estimating. However, we considered $1000 for recurring yearly maintenance/structure cost a reasonable assumption. Similarly, using the average of the last three years for other annually recurring cost can also result in either over or underestimation; yet this option was chosen to depict the most up-to-date cost for each recurring cost category.

Last but not least, the methodologies chosen to perform LCA and LCCA – BEES and NPV, also have their own limitations. In general, the life cycle approach for environmental or cost assessments do not consider interactions between the components (Sala, Farioli, & Zamagni, 2013), i.e., how the interactions between specific insulation and HVAC systems can further reduce energy consumption and hence further reduce costs. However, data on energy usage was measured and collected directly by the EEC at each facility assessment; this helps capture real-life energy saving, although the amount of actual savings would require further analysis. The impact scores for the impact categories derived by BEES also present high uncertainty, especially in the case of Eutrophication, due to the high level of uncertainty in the LCIA process (United States Environmental Protection Agency, 1995b). In terms of NPV, quantifying the true cost savings of intangible properties such as convenience of building's location or employees' work satisfaction due to upgrades/new facilities is not yet implemented on wide scale. Additionally, the up-front investment cost of the hybrid energy system at the Sisters facility might not accurately depict its true cost at the time of the study or future studies, once the technology matures and becomes available. Therefore, although the normalized NPV for the Sisters facility is higher than that of the Albany facility, further discounts for more availability of solar-geothermal technology and the significant energy usage and energy related environmental impacts should be considered for future designs of maintenance stations.

5.0 CONCLUSION

By performing Life Cycle Assessment and Life Cycle Cost Analysis on the two cases – the Albany and Sisters maintenance facilities, some significant insights on environmental impacts related to energy and building materials, as well as cost saving opportunities have been observed. The majority of the results either agree with the body of existing literature or can be explained by the nature of the operations at ODOT. Therefore, the results obtained here can pave the way for further analysis in the future, so that particular components can be analyzed for alternative materials to reduce environmental impacts and explore opportunities for cost savings. The research team has also included the list of alternative materials, energy systems, and their related costs and usability in Appendix C and D.

The Best Practice Guide, which was derived from this report, contains the necessary information for ODOT's designers to formulate the basic design factors that would influence environmental impacts and cost performances when approaching new maintenance facilities' design challenges. In addition, guidelines on different assessment methods using from simple methods such as building codes and certification to performing LCA and LCCA are also provided. This also assists ODOT in the future to perform trade-off analysis when decisions on choosing which project, location, or specific materials or systems must be made. In addition, by using the Best Practice Guide, ODOT can assess more varieties of maintenance stations and other facilities with similar functions.

6.0 REFERENCES

Senate Bill 79, 75th Oregon Legislative Assembly. (2009). Retrieved from https://olis.leg.state.or.us/liz/2009R1/Downloads/MeasureDocument/SB79/A-Engrossed

Adalberth, K. (1997). Energy use during the life cycle of buildings: a method. *Building and Environment, 32*(4), 317–320. DOI: 10.1016/S0360-1323(96)00068-6

Allouhi, A., El Fouih, Y., Kousksou, T., Jamil, A., Zeraouli, Y., & Mourad, Y. (2015). Energy consumption and efficiency in buildings: current status and future trends. *Journal of Cleaner Production*, *109*, 118–130. DOI: 10.1016/j.jclepro.2015.05.139

Al-Sulaiman, F. A., Hamdullahpur, F., & Dincer, I. (2012). Performance assessment of a novel system using parabolic trough solar collectors for combined cooling, heating, and power production. *Renewable Energy, 48*, 161–172. DOI: 10.1016/j.renene.2012.04.034

Althaus, H.-J., Hischier, R., Doka, G., Bauer, Ch., Dones, R,….Loerincik, Y. (2007). *Implementation of life cycle impact assessment methods Data v20 (2007)* (Publication No 3 (INIS-CH--10091)). Frischknecht, R., & Jungbluth, N. (Eds.). Switzerland Retrieved from www.iaea.org/inis/collection/NCLCollection Store/_Public/41/028/41028089.pdf

American Society of Heating, R., Air-Conditioning, E., American National Standards, I., & Illuminating Engineering Society of North, A. (2016). *Energy standard for buildings except low-rise residential buildings*.

American Society for Testing and Materials. (2015). *ASTM Volume 04.11 Building Constructions (I): E72-E2110* (Vols. 1–04.11). West Conshohocken, PA.

American Society for Testing and Materials. (2010). *Standard test method for determining air leakage rate by fan pressurization* (ASTM E779). DOI: 10.1520/E779-10

American Society for Testing and Materials. (2011). *Practice for applying analytical hierarchy process (AHP) to multi-attribute decision analysis of investments related to buildings and building systems* (ASTM E1765). DOI: 10.1520/E1765-11.

American Society for Testing and Materials. (2011). *Standard test method for determining air Lleakage of air barrier assemblies* (ASTM E2357). DOI: 10.1520/E2357-11.

American Society for Testing and Materials. (2012). *Standard test method for water in organic liquids by coulometric Karl Fischer titration* (ASTM E1074). DOI: 10.1520/E1064-12.

American Society for Testing and Materials. (2012). *Standard practice for measuring cost risk of buildings and building systems and other constructed projects* (ASTM E1946). DOI: 10.1520/E1946-12.

American Society for Testing and Materials. (2012). *Standard guide for summarizing the economic impacts of building-related projects* (ASTM E2204). DOI: 10.1520/E2204-12.

American Society for Testing and Materials. (2013). *Standard test method for air permeance of building materials* (ASTM E2178). DOI: 10.1520/E2178-13.

American Society for Testing and Materials. (2015). *Standard practice for measuring life-cycle costs of buildings and building systems* (ASTM E917). DOI: 10.1520/E0917-15.

American Society for Testing and Materials. (2015). *Standard practice for measuring benefit-to-cost and savings-to-investment ratios for buildings and building systems* (ASTM E964). DOI: 10.1520/E0964-15.

American Society for Testing and Materials. (2015). *Standard practice for measuring internal rate of return and adjusted internal rate of return for investments in buildings and building systems* (ASTM E1057). DOI: 10.1520/E1057-15.

American Society for Testing and Materials. (2015). *Standard practice for measuring payback for investments in building and building systems* (ASTM E1121) DOI: 10.1520/E1121-15.

American Society for Testing and Materials. (2015). *Standard guide for selecting economic methods for evaluating investments in buildings and building systems* (ASTM E1185). DOI: 10.1520/E1185-15.

American Society for Testing and Materials. (2015). *Standard guide for selecting techniques for treating uncertainty and risk in the economic valuation of buildings and building systems* (ASTM E1369). DOI: 10.1520/E1369-15.

Architecture 2030. (2002). The 2030 Challenge, Architecture 2030. Retrieved February 24, 2016, from www.architecture2030.org/2030_challenges/2030-challenge/

Ardente, F., Beccali, G., Cellura, M., & Lo Brano, V. (2005). Life cycle assessment of a solar thermal collector. *Renewable Energy*, *30*(7), 1031–1054. DOI:10.1016/j.renene.2004.09.009

Athena Sustainable Materials Institute. (n.d.). Impact Estimator for Buildings (Version Version 5.1 Build 01) [Computer software]. Retrieved March 4, 2016, from http://calculatelca.com/software/impact-estimator/

Ayoub, N., Musharavati, F., Pokharel, S., & Gabbar, H. A. (2015). Risk based life cycle assessment conceptual framework for energy supply systems in large buildings. *Journal of Cleaner Production*, *107*, 291–309. DOI: 10.1016/j.jclepro.2015.04.075

Bakst, J. S., Wynn, L., Lee, E., United States., & United States. (1995). *Guidelines for assessing the quality of life-cycle inventory data*. Washington, DC: United States Environmental Protection Agency, Solid Waste and Emergency Response.

Berger, M., van der Ent, R., Eisner, S., Bach, V., & Finkbeiner, M. (2014). Water Accounting and Vulnerability Evaluation (WAVE): Considering Atmospheric Evaporation Recycling and the Risk of Freshwater Depletion in Water Footprinting. *Envirnomental Science and Technology -Washington, D.C.-, 48*(8), 4521-4528. DOI: 10.1021/es404994t

Boise Cascade Wood Products, L.L.C. (n.d.). Weights of Building Materials – Pounds per Square Foot [PSF]. Retrieved October 2, 2017, from https://www.bc.com/resources/ge-1-weights-of-building-materials/

Bolin, C. A., & Smith, S. T. (2011). Life cycle assessment of borate-treated lumber with comparison to galvanized steel framing. *Journal of Cleaner Production*, *19*(6), 630–639. DOI: 10.1016/j.jclepro.2010.12.005

Bösch, M. E., Hellweg, S., Huijbregts, M. A. J., & Frischknecht, R. (2007). Applying cumulative exergy demand (CExD) indicators to the ecoinvent database. *Int J Life Cycle Assess The International Journal of Life Cycle Assessment, 12*(3), 181-190. DOI: 10.1065/lca2006.11.282

Boulay, A.-M., Bulle, C., Bayart, J.-B., Deschênes, L., & Margni, M. (2011). Regional characterization of freshwater use in LCA: modeling direct impacts on human health. *Environmental Science & Technology*, *45*(20), 8948–8957. DOI: 10.1021/es1030883

Buys, A., Bendewald, M., & Tupper, K. (2011). Life-Cycle Cost Analysis: Is it Worth the Effort? *Transactions- American Society of Heating Refrigerating and Air Conditioning Engineers, 117*, LV-11-C067.

California Building Standards Commission,. (2013). *2013 California green building standards code: CALGreen: California code of regulations, Title 24, Part 11*.

Carlisle, E. A. (2015, February 23). ODOT Sisters Maintenance Building – Taking the Long View [Web log post]. Retrieved January 24, 2016, from www.rweng.com/blogpost/odot-sisters-maintenance-building-taking-the-long-view/

Carnegie Mellon University. (n.d.). CMU - Economic Input-Output Life Cycle Assessment - Carnegie Mellon University. Retrieved December 31, 2016, from www.eiolca.net/

CML-Department of Industrial Ecology. (2016, September 5). CML-IA Characterisation Factors. Retrieved October 7, 2017, from https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors

Charette, R. P., Marshall, H. E., & National Institute of Standards and Technology (États-Unis). (1999). *UNIFORMAT II elemental classification for building specifications, cost estimating, and cost analysis*.

Construction Specifications Institute. (n.d.). MasterFormat Number & Titles. Retrieved February 8, 2016, from www.csinet.org/Home-Page-Category/Formats/MasterFormat

Construction Specifications Institute. (n.d.). Which do I use, UniFormat or MasterFormat?. Retrieved February 15, 2016, from www.csinet.org/Home-Page-Category/Formats/MasterFormat

Curran, M. A., Mann, M., & Norris, G. (2005). The international workshop on electricity data for life cycle inventories. *Journal of Cleaner Production*, *13*(8), 853–862. DOI: 10.1016/j.jclepro.2002.03.001

Department of Administrative Services. (2016). *Department of Administrative Services Policy Manual* (No. 107-011-010) (United States, State of Oregon, DAS). Salem, OR: DAS.

Davis, M., Coony, R., Gould, S., & Daly, A. (2005). Guidelines for Life Cycle Cost Analysis (Tech.). Stanford, CA: Stanford University Land & Buildings. Retrieved from https://sustainable.stanford.edu/sites/default/files/Guidelines_for_Life_Cycle_Cost_Analysis.pdf.

de Gracia, A., Navarro, L., Castell, A., Boer, D., & Cabeza, L. F. (2014). Life cycle assessment of a ventilated facade with PCM in its air chamber. *Solar Energy Phoenix Arizona Then New York-*, *104*, 115-123. DOI: 10.1016/j.solener.2013.07.023

Fabrycky, W. J., & Blanchard, B. S. (1991). *Life-cycle cost and economic analysis*. Englewood Cliffs, N.J.: Prentice Hall

Findings and Goals Regarding Sustainability, ORS 184.423. (2013). Retrieved March 4, 2016, from www.oregonlaws.org/ors/184.423

Fuller, S. K., Fuller, S. K., & National Institute of Standards and Technology (U.S.). (1996). *Life-cycle costing manual for the federal energy management programs*. Retrieved on January 12, 2009.

General Administration. (2010). Implementation of RCW 39.35D High Performance Green Buildings (Rep.). WA. Retrieved from https://www.digitalarchives.wa.gov/do/E47F376C44477DF352C9BFCCE7D7805C.pdf.

Ghattas, Randa, Gregory, Jeremy, Noori, Mehdi, Miller, T. Reed, Olivetti, Elsa, & Greene, Suzanne. (2013). *Life Cycle Assessment for Residential Buildings: A Literature Review and Gap Analysis*.

Goedkoop, M., Heijungs, R., Huijbregts, M., Schryver, A. D., Struijs, J., & Zelm, R. (2013). *ReCiPe 2008*. Retrieved from https://www.pre-sustainability.com/download/ReCiPe_main_report_MAY_2013.pdf

GPA Architects LLC. (2011, September 8). *ODOT Sisters Maintenance Station Relocation* (Project No. 10-001) [Architectural Drawing]. Retrieved from GPA Architects LLC Portland, OR.

GPA Architects LLC. (2012, December 14). *ODOT Sisters Maintenance Station Relocation Record Drawing.* [Architectural Drawing]. Retrieved from GPA Architects LLC Portland, OR.

Green building council Australia. (n.d.). Retrieved October 7, 2017, from www.new.gbca.org.au/green-star/

Green Building Initiative. Home Page. (n.d.). Retrieved March 2, 2016, from www.thegbi.org/

Green Globes. (2015). Green Globes for New Construction - Technical Reference Manual (Publication No. 1.4). Green Globes, NC. Retrieved from https://www.thegbi.org/files/training_resources/Green_Globes_NC_Technical_Reference_Manual.pdf.

Hammond, P. J. (2008). 2008 Sustainability Plan and Progress Report Update (Publication). Olympia, WA: Washington State Department of Transportation. Retrieved from www.wsdot.wa.gov/NR/rdonlyres/A66BD61B-0CB7-48F3-9403-D2542CE2B7E5/0/2008SustainabilityPlanandProgressReportUpdate_091409_final.pdf

Hernandez, P. (2014, October 7). BIRDS Is for Sustainability: New NIST Tool for Evaluating Building Performance, Trade-offs. Retrieved February 8, 2016, from https://www.nist.gov/news-events/news/2014/10/birds-sustainability-new-nist-tool-evaluating-building-performance-trade

Heravi, G., & Esmaeeli, A. N. (2014). Fuzzy Multicriteria Decision-Making Approach for Pavement Project Evaluation Using Life-Cycle Cost/Performance Analysis. *Journal of Infrastructure Systems, 20,* 2, 4014002. DOI: 10.1061/(ASCE)IS.1943-555X.0000170

Hong, T., Ji, C., Jang, M., Park, H., & Jang, M. (2014). Assessment model for energy consumption and greenhouse gas emissions during building construction. *Journal of Management in Engineering, 30,* 2, 226-235. DOI: 10.1061/(ASCE)ME.1943-5479.0000199

Humphries, C. J. M., & Pelot, R. (2014). A Multicriteria Decision Analysis Model and Risk Assessment Framework for Carbon Capture and Storage. *Risk Analysis, 34,* 9, 1720-1737. DOI: 10.1111/risa.12211

Inoue, Y., & Katayama, A. (2011). Two-scale evaluation of remediation technologies for a contaminated site by applying economic input-output life cycle assessment: Risk-cost, risk-energy consumption and risk-CO_2 emission. *Journal of Hazardous Materials, 192,* 3, 1234-1242. DOI: 10.1016/j.jhazmat.2011.06.029

International Energy Agency. (2013). Transition to sustainable buildings - strategies and opportunities to 2050 (Publication). Paris, France. Retrieved from https://www.iea.org/publications/freepublications/publication/Building2013_free.pdf.

International Living Future Institute. (2016). Living Building Challenge 3.0. Retrieved from https://living-future.org/wp-content/uploads/2016/12/Living-Building-Challenge-3.0-Standard.pdf

International Living Future Institute. (n.d.). International Living Future Institute Homepage. Retrieved March 2, 2016, from www.living-future.org/

Islam, H., Jollands, M., Setunge, S., Haque, N., & Bhuiyan, M. A. (January 01, 2015). Life cycle assessment and life cycle cost implications for roofing and floor designs in residential buildings. *Energy and Buildings, 104,* 250-263. DOI: 10.1016/j.enbuild.2015.07.017

International Organization for Standardization. (2000). *Environmental management - life cycle assessment - life cycle impact assessment* (ISO 14042:2000). Retrieved from: https://www.iso.org/standard/23153.html

International Organization for Standardization. (2000). *Environmental management - life cycle assessment - life cycle interpretation* (ISO 14043:2000). Retrieved from: https://www.iso.org/standard/23154.html

International Organization for Standardization. (2006). *Environmental management - life cycle assessment - principles and framework* (ISO 14040:2006). Retrieved from: https://www.iso.org/standard/37456.html

International Organization for Standardization. (2006). *Environmental management - life cycle assessment - requirements and guidelines* (ISO 14044:2006). Retrieved from: https://www.iso.org/standard/72357.html

Jefferies, D., Muñoz, I., Hodges, J., King, V. J., Aldaya, M., Ercin, A. E., Milà, . C. L., ... Hoekstra, A. Y. (September 01, 2012). Water Footprint and Life Cycle Assessment as approaches to assess potential impacts of products on water consumption. Key learning points from pilot studies on tea and margarine. *Journal of Cleaner Production, 33,* 155-166. DOI: 10.1016/j.jclepro.2012.04.015

Kenisarin, M., & Mahkamov, K. (2007). Solar energy storage using phase change materials. *Renewable and Sustainable Energy Reviews, 11*(9), 1913-1965. doi:10.1016/j.rser.2006.05.005

Kneifel, J. (2010). Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. *Energy and Buildings, 42,* 3, 333-340. DOI: 10.1016/j.enbuild.2009.09.011

Koroneos, C., & Tsarouhis, M. (2012). Exergy analysis and life cycle assessment of solar heating and cooling systems in the building environment. *Journal of Cleaner Production, 32*, 52-60. DOI: 10.1016/j.jclepro.2012.03.012

Lavappa, P. D., & Kneifel, J. D. (2015). Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis – 2015 Annual Supplement to NIST Handbook 135. *NIST Interagency/Internal Report (NISTIR) - 85-3273-30*. Retrieved from https://www.nist.gov/publications/energy-price-indices-and-discount-factors-life-cycle-cost-analysis-150-2015-annual

Levy, B. S. (2011). *Occupational and Environmental Health: Recognizing and Preventing Disease and Injury*: Oxford University Press.

Lorand, R., Cohen, J. M., Mello, J., Panich, D., National Research Council (U.S.)., National Cooperative Highway Research Program,, American Association of State Highway and Transportation Officials,, ... New West Technologies, LLC. (2013). *Renewable energy guide for highway maintenance facilities*.

Martínez, E., Blanco, J., Jiménez, E., Saenz-Díez, J. C., & Sanz, F. (2015). Comparative evaluation of life cycle impact assessment software tools through a wind turbine case study. *Renewable Energy, 74,* 237-246. DOI: 10.1016/j.renene.2014.08.004

Motoshita, M., Itsubo, N., & Inaba, A. (2011). Development of impact factors on damage to health by infectious diseases caused by domestic water scarcity. *The International Journal of Life Cycle Assessment, 16,* 1, 65-73. DOI: 10.1007/s11367-010-0236-8

Nam, K., Chang, D., Chang, K., Rhee, T., & Lee, I.-B. (2011). Methodology of life cycle cost with risk expenditure for offshore process at conceptual design stage. *Energy*, *36*(3), 1554–1563. DOI:10.1016/j.energy.2011.01.005

Nathwani, J., & National Renewable Energy Laboratory (U.S.). (2004). *Geothermal technologies program: Buried treasure: the environmental, economic, and employment benefits of geothermal energy*. Golden, CO: National Renewable Energy Laboratory.

National Institute of Building Sciences. (n.d.). Life-Cycle Cost Analysis (LCCA). Retrieved April 11, 2016, from www.wbdg.org/resources/lcca.php

National Institute of Standards and Technology. (2010). BEES 3.0: Building for environmental and economic sustainability [Computer software]. Retrieved from https://www.nist.gov/services-resources/software/bees

Norris, G. A. (2001). Integrating life cycle cost analysis and LCA. *The International Journal of Life Cycle Assessment*, *6*(2), 118–120.

Oregon Department of Transportation. (2012). 2012 ODOT Sustainability Progress Report. Retrieved from http://library.state.or.us/repository/2013/201305131055111/2012.pdf

Oregon Department of Transportation. (2014). 2014 ODOT Sustainability Progress Report. Retrieved from http://library.state.or.us/repository/2013/201305131055111/ODOT_SUS_docs_Sustainability_Report_2014.pdf

Oregon Department of Transportation. (2016). *ODOT Sustainability Plan Volume II*. Oregon. Retrieved from https://www.oregon.gov/ODOT/Programs/TDD%20Documents/ODOT-Sustainability-Plan-Volume-2.pdf

Oregon Department of Transportation, & Oregon State University. (2015, July 23). Adjusting Asphalt Mixes for Increased Durability and Implementation of a Performance Tester to Evaluate Fatigue Cracking of Asphalt Concrete. Retrieved from https://www.oregon.gov/ODOT/Programs/ResearchDocuments/SPR785WP.pdf

Omer, A. M. (2008). Renewable building energy systems and passive human comfort solutions. *Renewable and Sustainable Energy Reviews*, *12*(6), 1562–1587. DOI: 10.1016/j.rser.2006.07.010

Oregon. (2007). *State energy efficient design (SEED) program: Guidelines for Oregon administrative rules, chapter 330, division 130*. Salem, Or.: Oregon Dept. of Energy.

Oregon Building Codes Division. (2008). Oregon Building Codes Division Green Building Codes Division. Retrieved February 24, 2016, from https://www.bcd.oregon.gov/green.html

Oregon Department of Energy. (n.d.). State Energy Efficient Design Program. Retrieved February 24, 2016, from https://www.oregon.gov/energy/energy-oregon/Pages/SEED.aspx

Oregon State University. (n.d.). Green Building. Retrieved October 4, 2017, from www.fa.oregonstate.edu/sustainability/operations/green-building

Oró, E., Gil, A., de Gracia, A., Boer, D., & Cabeza, L. F. (2012). Comparative life cycle assessment of thermal energy storage systems for solar power plants. *Renewable Energy*, *44*, 166–173. DOI:10.1016/j.renene.2012.01.008

Parallelus. (n.d.). J.E. Foster. Retrieved February 24, 2016, from www.jefoster.com/

Pascale, A., Urmee, T., & Moore, A. (2011). Life cycle assessment of a community hydroelectric power system in rural Thailand. *Renewable Energy*, *36*(11), 2799–2808. DOI: 10.1016/j.renene.2011.04.023

Patel, M. (2003). Cumulative energy demand (CED) and cumulative CO_2 emissions for products of the organic chemical industry. *Energy*, *28*(7), 721–740. DOI: 10.1016/S0360-5442(02)00166-4

Peurifoy, R. L., & Oberlender, G. D. (2001). Estimating construction costs (5th ed., Revised). New York, NY: McGraw-Hill.

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the environmental impacts of freshwater consumption in LCA. Environmental Science & Technology, 43(11), 4098–4104. DOI: 10.1021/es802423e

PRé Sustainability. (n.d.). SimaPro LCA [Computer software]. Retrieved February 25, 2016, from https://simapro.com/about/

PRé Sustainability, Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., & Meijer, E. (2016). Introduction to LCA with SimaPro (Ser. 5.2, Manual). San Francisco, CA: Creative Commons. Retrieved October 9, 2017, from https://www.pre-sustainability.com/download/SimaPro8IntroductionToLCA.pdf.

Principi, P., & Fioretti, R. (2014). A comparative life cycle assessment of luminaires for general lighting for the office – compact fluorescent (CFL) vs Light Emitting Diode (LED) – a case study. *Journal of Cleaner Production*, *83*, 96–107. DOI: 10.1016/j.jclepro.2014.07.031

Reza, B., Sadiq, R., & Hewage, K. (2011). Sustainability assessment of flooring systems in the city of Tehran: An AHP-based life cycle analysis. *Construction and Building Materials*, *25*(4), 2053–2066. DOI: 0.1016/j.conbuildmat.2010.11.041

Ridoutt, B. G., & Pfister, S. (2010). A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Global Environmental Change*, *20*(1), 113–120. DOI: 10.1016/j.gloenvcha.2009.08.003

Riggs, J. L., & Jones, D. (1990). Flowgraph representation of life cycle cost methodology-a new perspective for project managers. *IEEE Transactions on Engineering Management*, *37*(2), 147–152. DOI: 10.1109/17.53719

Rijkswaterstaat, Royal HaskoningDHV, & Cenosco. (n.d.). What is DuboCalc | Dubo Calc Portal. Retrieved July 13, 2018, from https://www.dubocalc.nl/en/what-is-dubocalc/

Russo, G., Anifantis, A. S., Verdiani, G., & Mugnozza, G. S. (2014). Environmental analysis of geothermal heat pump and LPG greenhouse heating systems. *Biosystems Engineering*, *127*, 11–23. DOI: 10.1016/j.biosystemseng.2014.08.002

Sala, S., Farioli, F., & Zamagni, A. (2013). Life cycle sustainability assessment in the context of sustainability science progress (part 2). *The International Journal of Life Cycle Assessment*, *18*(9), 1686–1697. DOI: 10.1007/s11367-012-0509-5

Säynäjoki, A., Heinonen, J., & Junnila, S. (2012). A scenario analysis of the life cycle greenhouse gas emissions of a new residential area. *Environmental Research Letters*, *7*(3), 34037. DOI: 10.1088/1748-9326/7/3/034037

Selim, Y. P., & Bayram, D. (2015). Life cycle costing model based on target costing and activity-based costing method and a model proposal. *European Scientific Journal*, *2*, 121.

Shameri, M. A., Alghoul, M. A., Sopian, K., Zain, M. F. M., & Elayeb, O. (2011). Perspectives of double skin façade systems in buildings and energy saving. *Renewable and Sustainable Energy Reviews*, *15*(3), 1468–1475. DOI: 10.1016/j.rser.2010.10.016

Sharrard, A. L., Matthews, H. S., & Roth, M. (2007). Environmental implications of construction site energy use and electricity generation. *Journal of Construction Engineering and Management*, *133*(11), 846–854.

Smith, C., Burrows, J., Scheier, E., Young, A., Smith, J., Young, T., & Gheewala, S. H., ... Young, T. (2015). Comparative life cycle assessment of a thai island's diesel/pv/wind hybrid microgrid. *Renewable Energy*, *80*, 85–100. DOI: 10.1016/j.renene.2015.01.003

State of Oregon. (n.d.). Energy Code Program. Retrieved October 7, 2017, from https://www.oregon.gov/bcd/codes-stand/Pages/energy-efficiency.aspx

Sustainability Defined, ORS - 184.421. (2013). Retrieved March 4, 2016, from www.oregonlaws.org/ors/184.421

Tähkämö, L., & Halonen, L. (2015). Life cycle assessment of road lighting luminaires – Comparison of light-emitting diode and high-pressure sodium technologies. *Journal of Cleaner Production*, *93*, 234–242. DOI: 10.1016/j.jclepro.2015.01.025

The Oregonian. (n.d.). Tracking House Bill 2950 in the Oregon Legislature. Retrieved October 7, 2017, from https://gov.oregonlive.com/bill/2017/HB2950/

Thiel, C. L., Campion, N., Landis, A. E., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). A materials life cycle assessment of a net-zero energy building. *Energies*, *6*(2), 1125–1141. DOI: 0.3390/en6021125

Tsai, W.-H., Yang, C.-H., Chang, J.-C., & Lee, H.-L. (2014). An Activity-Based Costing decision model for life cycle assessment in green building projects. *European Journal of Operational Research*, *238*(2), 607–619. DOI: 10.1016/j.ejor.2014.03.024

Turner, Barber, & Barrett. (1995a, January 20). *ODOT Albany Maintenance Facility Drawings*. [Architectural Drawing]. Retrieved from Turner, Barber, & Barrett, Albany, OR.

Turner, Barber, & Barrett. (1995b, January 20). *Project Manual for Oregon Department of Transportation Maintenance Facility*. [Architectural Drawing]. Retrieved from Turner, Barber, & Barrett, Albany, OR.

United States. (1997). *Life-Cycle Impact Assessment: A Conceptual Framework Key Issues, And Summary Of Existing Methods ... U.S. Environmental Protection Agency ... July 1995*. Place of publication not identified: publisher not identified.

United States Department of Energy. (2011). Buildings Energy Data Book - OpenEI DOE Open Data. Retrieved July 13, 2018, from https://openei.org/doe-opendata/dataset/buildings-energy-data-book

United States Department of Energy. (n.d.-a). Building Life Cycle Cost Programs. Retrieved April 15, 2016, from http://energy.gov/eere/femp/building-life-cycle-cost-programs

United States Department of Energy. (n.d.-b). Clean Renewable Energy Bonds (CREBs). Retrieved February 24, 2016, from https://www.energy.gov/savings/clean-renewable-energy-bonds- crebs

United States Department of Energy. (2014). *Cost Estimating Guide*. Washington D.C. Retrieved from https://www.directives.doe.gov/directives-documents/400-series/0413.3-EGuide-21A/@@images/file

United States Environmental Protection Agency. (2006a). Emissions & Generation Resource Integrated Database (eGRID). Retrieved February 26, 2016, from https://www.epa.gov/energy/emissions-generation-resource-integrated-database-egrid

United States Department of Energy. (n.d.-c). Federal Energy Management Tools. Retrieved February 11, 2016, from http://energy.gov/eere/femp/federal-energy-management-tools

United States Environmental Protection Agency. (2010). Federal Green Construction Guide for Specifiers. Retrieved November 20, 2015, from www.wbdg.org/ffc/epa/federal-green-construction-guide-specifiers

United States Environmental Protection Agency. (1995a). *Guidelines for assessing the quality of life-cycle inventory analysis* (No. EPA530- R-95-010) (p. 105).

United States Environmental Protection Agency. (2006b). *Life cycle assessment: Principles and practice* (Publication No. EPA/600/R-06/060). Washington, D.C.

United States Environmental Protection Agency. (1995b). *Life cycle impact assessment: a conceptual framework, key issues, and summary of existing methods* (No. EPA-452/R-95-002) (p. 230). Research Triangle Park, NC.

United States Department of Energy. (2017, May 21). Local Laws and Incentives. Retrieved September 6, 2017, from https://www.afdc.energy.gov/laws/local_example

United States. Environmental Protection Agency. (2016, March 29). Municipal Solid Waste. Retrieved September 1, 2017, from https://archive.epa.gov/epawaste/nonhaz/municipal /web/html/

United States Green Building Council. (2009). LEED 2009 for New Construction - current version | U.S. Green Building Council. Retrieved from http://www.usgbc.org/resources/leed-new-construction-v2009-current-version

United States Green Building Council. (2018, July). LEED v4 for Building Design and Construction - current version | U.S. Green Building Council. Retrieved from http://www.usgbc.org/resources/leed-v4-building-design-and-construction-current-version

United States Green Building Council. (n.d.-a). About USGBC | USGBC. Retrieved July 13, 2018, from https://new.usgbc.org/about

United States Green Building Council. (n.d.-b). LEED | USGBC. Retrieved July 13, 2018, from https://new.usgbc.org/leed

Van Ooteghem, K., & Xu, L. (2012). The life-cycle assessment of a single-storey retail building in Canada. *Building and Environment*, *49*, 212–226. DOI: 10.1016/j.buildenv.2011.09.028

Venner Consulting., Parsons, Brinckerhoff, Quade & Douglas., AASHTO Center for Environmental Excellence., United States., & National Cooperative Highway Research Program. (2004). *Environmental stewardship practices, procedures, and policies for highway construction and maintenance*. Washington, D.C.: American Association of State Highway and Transportation Officials, Center for Environmental Excellence.

Vigon, B. W. (1994). *Life-cycle assessment: inventory guidelines and principles*. Boca Raton: London: Lewis.

Waghmode, L., Sahasrabudhe, A., & Kulkarni, P. (2010). Life cycle cost modeling of pumps using an activity-based costing methodology. *Journal of Mechanical Design*, *132*(12), 121006–121006. DOI: 10.1115/1.4002970

Washington Department of Corrections. (2016). LEED™ Projects | Washington State Department of Corrections. Retrieved July 13, 2018, from http://www.doc.wa.gov/about/business/capital-planning/leed.htm

Yu, D., Tan, H., & Ruan, Y. (2011). A future bamboo-structure residential building prototype in China: Life cycle assessment of energy use and carbon emission. *Energy and Buildings*, *43*(10), 2638–2646. DOI: 10.1016/j.enbuild.2011.06.013

Zabalza Bribián, I., Aranda Usón, A., & Scarpellini, S. (2009). Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building and Environment*, *44*(12), 2510–2520. DOI: 10.1016/j.buildenv.2009.05.001

APPENDIX A – TOOLS AND AVAILABLE SOFTWARE FROM ENERGY.GOV

TITLE	DESCRIPTION	TYPE	CATEGORY
Water Project Screening Tool	This tool helps federal sites identify a comprehensive suite of water efficiency projects, especially targeted at energy savings performance contracts and utility energy service contracts.	Data	Water Efficiency
Solar Hot Water System Calculator	This FEMP online tool estimates the size and costs of solar systems.	Calculator	Renewable Energy
Search for Efficient Technologies and Products for Federal Facilities	This tool allows users to search for technologies and products by efficiency program or topic.	Database	Technology Deployment
Savings Calculator for ENERGY STAR-Qualified Appliances	This ENERGY STAR calculator allows Federal agencies to enter their own input values to estimate energy and cost savings for energy-efficient appliances.	Calculator	Energy-Efficient Products
Rooftop Unit Comparison Calculator	This Pacific Northwest National Laboratory calculator simulates the energy usage of both a high efficiency and a standard efficiency air conditioner and compares their energy and economic performance.	Calculator	Energy-Efficient Products
RESFEN	This software from Lawrence Berkeley National Laboratory assists with estimating heating and cooling costs.	Software	Sustainable Buildings and Campuses
Prioritization Tool	The Prioritization Tool provides analytical support for its programmatic decision-making and to further accelerate the transformation of the U.S. building energy efficiency sector.	Calculator	Sustainable Buildings and Campuses

MotorMaster+	This software from the National Electrical Manufacturers Association aids with identifying the most efficient action for a given repair or motor purchase decision.	Software	Sustainable Buildings and Campuses
Low Standby Power Product List	The Federal Energy Management Program's (FEMP) Low Standby Power Product List features manufacturer-supplied standby power data for three types of computers: desktop, thin client, and workstation.	Application	Energy-Efficient Products
Life Cycle Cost Estimate for an ENERGY STAR-Qualified Gas Residential Furnace	This ENERGY STAR calculator allows Federal agencies to enter their own input values to estimate energy and cost savings for energy-efficient gas residential furnaces.	Calculator	Energy-Efficient Products
General Services Administration (GSA) Carbon Footprint and Green Procurement Tool	This voluntary tool was developed by GSA to assist agencies in managing GHGs as required by E.O. 13514.	Calculator	Sustainable Buildings and Campuses
FEMP Technology Deployment Case Studies Map	This map shows case studies of efficient technologies deployed in federal applications across the nation.	Map	Technology Deployment
FEMP Investment Grade Audit Tool	This tool is used by energy service companies during the ESPC ENABLE process.	Calculator	Sustainable Buildings and Campuses
FEMP EISA 432 Compliance Tracking System	This FEMP tool tracks agency performance of energy and water evaluations, project implementation and follow-up measures, and annual building benchmarking requirements.	Database	Facility Reporting

Federal Renewable Energy Project Potential by Technology	These maps and graphs illustrate electricity consumption at 7,000 covered federal facilities and the potential for renewable energy technology opportunities and federal incentives at these sites.	Map	Renewable Energy Projects
Federal Energy Management Program Acquisition Guidance for Lighting Products	FEMP provides acquisition guidance and federal efficiency requirements across a variety of product categories, including exterior lighting. This tool uses search criteria to provide only relevant lighting products from the FEMP Acquisition Guidance Product List.	Software	Outdoor Solid State Lighting
Facility Energy Decision System	This Pacific Northwest National Laboratory software provides a comprehensive, integrated, resource-planning approach to selecting technologies with a minimum life cycle cost.	Software	Sustainable Buildings and Campuses
ESCO Selector	This tool helps agencies create a notice of opportunity that complies with federal requirements and meets agency needs.	Form	Energy Savings Performance Contracts
eProject Builder	This Lawrence Berkeley Laboratory online tool enables energy service companies and their customers to update and track project-level information, generate basic reports, and benchmark projects against existing data.	Software	Energy Savings Performance Contracts
EnergyPlus	The EnergyPlus Simulation Program helps building designers and owners save money, reduce energy, and improve indoor air quality.	Software	Sustainable Buildings and Campuses
Energy Cost Calculator for Commercial Heat Pumps	This FEMP calculator allows Federal agencies to enter their own input values to estimate energy and cost savings for commercial heat pumps.	Calculator	Energy-Efficient Products

Distributed Generation Energy Technology Capital Costs	This National Renewable Energy Laboratory Web section offers charts that indicate capital cost estimates for distributed generation renewable energy technologies.	Data	Renewable Energy Projects
Comprehensive Annual Energy Data and Sustainability Performance	This FEMP tool allows users to view and download publicly available data tables of agency energy and water consumption and costs by end-use sector, efficiency investment information, and progress toward key goals.	Data	Facility Reporting
Compliance Certification Database	The Certification Database houses certification reports and compliance statements submitted by manufacturers for covered products and equipment subject to Federal conservation standards.	Database	Energy-Efficient Products
Building Life Cycle Cost Calculator (BLCC) 5 Program	This National Institute of Standards and Technology program helps compute and analyze capital investments in buildings.	Software	Sustainable Buildings and Campuses
Building Energy Software Tools Directory	This Building Technologies Office directory provides information on building software tools for evaluating energy efficiency, renewable energy, and sustainability in buildings.	Software	Sustainable Buildings and Campuses
Alternative Water Sources Map	This map provides information about rainwater harvesting regulations throughout the United States.	Map	Water Efficiency

APPENDIX B – LIST OF PRODUCTS (ENVIRONMENTAL DATA NEEDED IN ACCORDANCE WITH TABLE 1 OF ASTM E 2129)

a. Masonry

b. Finish Carpentry

c. Plastic Fabrications

d. Building Insulation

e. Roofing

f. Joint Sealers

g. Wood & Plastic Doors

h. Windows

i. Skylights

j. Glazed Curtain Wall

k. Gypsum Board

l. Tile

m. Acoustical Ceilings

n. Resilient Flooring

o. Carpet

p. Wall Coverings

q. Paints & Coatings

r. Toilet Compartments

s. Loading Dock Equipment

t. Office Equipment

u. Furnishings & Accessories

v. Renewable Energy Equipment

w. Elevators

x. Plumbing Fixtures and Equipment

y. HVAC Equipment

z. Lighting Equipment

APPENDIX C – ALTERNATIVE STRUCTURAL COMPONENTS AND CHARACTERISTCS

STRUCTURE	MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
Roof	Green roof	_A green roof has a substrate (soil or growing medium), and vegetation _Components involved in a vegetated roof: structural support, a high-quality waterproofing membrane, an anti-root barrier, a drainage layer, a water storage layer, a filtration layer, a substrate and, finally, plants on top. [1]	Provide a more stable environment on the roof; cooler when it is hot and warmer when it is cold, which can reduce cooling and heating requirements. Potential energy savings may help achieve carbon credits if available. [2]	IMPACTS: _Eutrophication (growing medium) _Abiotic depletion & ozone depletion (Waterproofing membrane) BENEFITS: _Reduction of SO_x, NO_x, PM, CO_2 _Improvement of storm water management _Biodiversity _Mitigate heat island effect _Agriculture, clean air, aesthetics [1], [2]	_Installation: $287,000 _Initial Premium: $114,238 _1st year Maintenance: $4,400 _Disposal: $4480 _-$7075 NPV; 6.5 years payback; 193.8% ROI for 50 year-life & 4.4% discount rate [2]	_Offer cooling effects in warm climate & tropical regions _Reduce CO_2 and improve air quality in urban cities [3]
	Concrete slab	Typically consists of a combination of a concrete slab and lightweight concrete made of expanded clay, in conjunction with insulation and additional waterproofing,	High thickness of roofing construction allows for effective insulation from outside temperatures and solar radiation. Uses significant more materials to	IMPACTS: _Human health (Aluminum in Soil) _Ecosystem and Natural Resources (Use of ferrous materials, NO_x, zinc, & coal) BENEFITS:	_Installation: $320 to $1200 per 100 square feet _Life Expectancy: 50 to 100+ years [5]	Due to low/no slope of concrete roofs, they are not typically recommended in climates where snow and heavy rains are common. Recommended in

STRUCTURE	MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
		such as bitumen. Overall thickness is typically around 14 inches total. [4]	construct roof when compared to other roofing options [4]	_Recycling potential [4]		areas prone to tornados or hurricanes. [6]
	Metal (steel, aluminum, galvanized)	Roofing system made from metal sheets or tiles. Many different types of systems that are available depending on application. Coatings typically need to be applied to prevent rust, to provide waterproofing, or to shield from heat. [7]	Unpainted metal roofs act as good solar reflectors but poor thermal emitters; painted metal roofing can achieve high solar reflectance and high thermal emittance providing more stable temperatures inside structure. [22]	IMPACTS: _Human health (Dioxin and NO) _Ecosystem and Natural Resources (Use of ferrous materials, NO_x, zinc, & coal) BENEFITS: _Recycling potential [4]	_Installation: $155 to $310 per 100 square feet _Life Expectancy: 50 years [5]	_Long lasting and relatively inexpensive roof. Poor thermal protection is provided _Labor intensive during installation. [5]
	Ceramic tiles	Interlocking ceramic tiles that are typically hung with nails in parallel columns. Typically very	Poor solar reflecting characteristics unless coated with special low solar reflective index	IMPACTS: _High amount of materials needed [5]	_Installation: $140 to $850 per 100 square feet _Life Expectancy: 50 years [5]	Due to high cost, difficulty of installation, and high weight, benefits are typically

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
			heavy and long lasting when compared to other roofing options. [7]	coating. Low solar reflective index indicates poor shielding from solar energy. [23]			attributed strictly to visual appeal. [5]
		Asphalt shingles	A type of roofing option which uses asphalt for waterproofing. Relatively low purchase and installation cost. [7]	High reflectivity provides effective solar reflectors which allows building to stay cool even it is hot outside. Uses minimal materials/resources to construct roof. [22]	IMPACTS: _Ecosystem (benzene-soluble particles) _Human health (fumes known to cause acute health effects from asphalt exposure) BENEFITS: _Low amount of materials needed [36]	_Installation: $20-140 per 100 square feet _Life Expectancy: 15 to 30 years [5]	Excellent inexpensive roofing option; allows inexpensive construction cost but has a low life expectancy. [5]
Walls	Insulation	Fiberglass	_A manmade material that is made of thin glass fiber. _Used for thermal insulation and sound proofing. _Used for both commercial and residential applications due to its lightweight,	Two common methods of using fiber glass are cutting out the shape needed and installing or spray-on fiberglass. At 3.5 inches thick, the fiberglass can reach an R-value of 11. The spray method can ensure	IMPACT: _Global Warming _Acidification[37]	The initial cost ranges from $331 to $882 depending on the desired R value. The uniform annual costs are between $1,000 and $2200 (also R value dependent). The total life cycle cost ranges	The payback on fiberglass insulation is shorter in colder climates. It can be used in warmer climates as well, but it would have a longer payback.[48]

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
			cost effective, and practical nature. [8]	that the insulation covers all areas, which would help with efficiency. [24]		between $2200 and $5000, also dependent on the R value. The colder the climate, the higher the life cycle cost.[48]	
		Mineral (rock or slag) wool	The term "mineral wool" typically refers to two types of insulation material: _Rock wool, a man-made material consisting of natural minerals like basalt or diabase. _Slag wool, a man-made material from blast furnace slag (the scum that forms on the surface of molten metal). [9]	Loose-fill and Blown-in insulation R value: 3.0-3.3 per inch [9]	IMPACTS: Human Health Impacts (Risk of Lung Cancer) BENEFITS: _Mineral wool is usually produced from 75% post-industrial recycled content. [38], [9]	Cost for 4" thick installation: $0.80 [49]	_When building code requires additional fire protection, mineral wool blow-in fiber is installed in stud cavities. _Can be installed without the use of a mechanical blower machine. The material can be crumpled by hand because it is a natural product. A drawback to this method is the fact that it can take considerably

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
							longer to install versus cellulose or fiberglass [59]
		Plastic fibers	Plastic fiber insulation material is primarily made from recycled plastic milk bottles (polyethylene terephthalate or PET). The fibers are formed into batt insulation similar to high-density fiberglass.[9]	The R-values of plastic fiber insulation vary with the batt's density, ranging from R-3.8 per inch at 1.0 lb./ft^3 density to R-4.3 per inch at 3.0 lb./ft^3 density. [9]	IMPACTS: _Human Toxicity BENEFITS: _Primarily made from recycled milk bottles [9]	$.48 per inch [49]	In many areas of the United States, plastic fiber insulation might not be readily available [60]
		Natural fiber	Some natural fibers -- including cotton, sheep's wool, straw, and hemp -- are used as insulation materials [9]	COTTON: Cotton insulation is available in batts with an R-value of R-3.4 per inch. SHEEPS WOOL: The thermal resistance or R-value of sheep's wool batts is about R-3.5 per inch STRAW:	IMPACTS: _ CO_2 Emissions throughout life cycle _Global Warming Potential [39]	COTTON: cotton insulation costs about 15-20% more than fiberglass batt insulation. SHEEPS WOOL: As for cost, Oregon Shepard sells for $2.75 per pound. For a 2x4 wall, providing R-	The payback on fiberglass insulation is shorter in colder climates. It can be used in warmer climates as well, but it would have a longer payback. [48]

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				Straw bales tested by Oak Ridge National Laboratory yielded R-values of R-2.4 to R-3.0 per inch. HEMP: Its R-value is about R-3.5 per inch of thickness [9]		13 insulation will cost about $0.67 per square foot, compared with $0.35 – 0.40 for fiberglass, $0.50 to 0.55 for cellulose, and $0.85 for cotton, according to Workman [50]	
		Cellulose (recycled newsprint)	Cellulose insulation is made from recycled paper products, primarily newsprint, and has a very high recycled material content, generally 82% to 85%. The paper is first reduced to small pieces and then fiberized, creating a product that packs tightly into building cavities,	R value per inch by Loose-Fill Insulation: 3.2-3.8 per inch [9]	IMPACTS: Made of recycled newsprint = low environmental impacts [9]	Loose Fill Insulation Installation Cost for 4" thick: $0.55 per inch [49]	_One small drawback of cellulose is the lack of an innate vapor retarder. Unlike natural rock wool and fiberglass, cellulose can become damaged if left wet for too long. _Require adequate additional insulation between joist

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			inhibits airflow. [9]				spans, in addition to a vapor-retardant material on the insulated side facing the conditioned space. [59]
		Expandable foam	Expanding foam is a product which is designed to expand and harden upon contact with the air. Latex, polyurethane, and a variety of other materials can serve as a base for this product, and waterproof, fire resistant, and other specialty versions are available. [10]	Low density SPF: R-Value of 3.6-4.0 Medium density SPF: R-Value of 5.8-6.8 [25]	Vapors and aerosols released during and after mixing can cause asthma, lung damage, other respiratory and breathing problems, skin and eye irritation, and cancer [40]	Service Life: 60 years [51]	Can be applied to all types of climes, although open-cell SPF is permeable to moisture, and may need an additional vapor retarder in cold-climate building applications. [51]
		Expanded polystyrene	Expanded polystyrene (EPS) and extruded polystyrene (XPS) are other polystyrene	The thermal resistance or R-value of polystyrene foam board depends on its density, and	Water footprint and global warming potential. [41]	Life Expectancy: 60 years [52]	High insulating value for relatively little thickness. Can block thermal short circuits

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			insulation materials similar to MEPS. XPS is most commonly used as foam board insulation. EPS is commonly produced in blocks. Both MEPS and XPS are often used as the insulation for structural insulating panels (SIPs) and insulating concrete forms (ICFs). [9]	ranges from R-3.8 to R-5.0 per inch. Polystyrene loose-fill or bead insulation typically has a lower R-value (around R-2.3 per inch) compared to the foam board. [9]			when installed continuously over frames or joists. [9]
	Support	Concrete	Concrete is a mixture of paste and aggregates, or rocks. The paste, composed of Portland cement and water, coats the surface of the fine (small) and coarse (larger) aggregates. Through a	Concrete Block 4" R Value: 0.80Poured Concrete R Value: 0.08 per inch [26]	Cement was found to be the primary source of CO_2 emissions [42]	Energy cost savings of a steel framed building with lightly framed exterior walls are higher to that of a concrete framed building with concrete exterior walls in 6 major US cities.[53]	Masonry walls cannot be constructed to an unlimited height - broadly speaking, most are considered stable only to a height of 10-15 ft. (3 - 4m). To construct a masonry wall higher than that, a

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
			chemical reaction called hydration, the paste hardens and gains strength to form the rock-like mass known as concrete. [11]				special wall that has intermediate structural members to support the wall is required.[61]
		Masonry	Masonry cement usually consists of a mixture of Portland cement and hydrated lime. At present, the manufacturers of cement have gone into the production of prepared masonry cements by adding such materials as finely ground limestone, finely Found shale, or clay refuse from common clay ware manufacturing plants. [12]	Masonry 4" R Value: 0.80 [27]	IMPACT: _CO_2 Emissions _Produce particulate matter in air [43]	Masonry, 70 lb. bag, T.L. lots: $12/bag [49]	Masonry walls cannot be constructed to an unlimited height - broadly speaking, most are considered stable only to a height of 10-15 ft. (3 - 4m). To construct a masonry wall higher than that, a special wall that has intermediate structural members to support the wall is required. [61]

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
		Wood	The chemical properties of wood are inherently complex. Perhaps one of the biggest advantages of using wood as a building material is that it is a natural resource, making it readily available and economically feasible. Wood is highly machinable, and can be fabricated into all kinds of shapes and sizes to fit practically any construction need. [13]	Houses built with wood-based systems required about 15–16% less total energy for non-heating/cooling purposes than thermally comparable houses employing alternative steel- or concrete based building systems. Cedar Logs and Lumber R Value per Inch: 1.33 Softwood Lumber 2x4 R Value: 4.38 per thickness [28]	The net GHG emissions associated with wood-based houses were 20–50% lower than those associated with thermally comparable houses employing steel- or concrete-based building systems [28]	ex: Timber framing (4"x4"): $3.70 [54]	The type of wood that can be used is dependent on the exposure of wood to weather. Wood can also be treated based on the climate of area (pressure treat, fire resistant, etc.). [62]
	Exterior Finish	Wood	See Wood for Support above [13]	Hardboard R Value: 0.34 at 1/2" thickness Plywood R Value: 0.77 at 5/8" [26]	_The GHG benefits of substituting wood for non-wood building materials are generally greater than the energy benefits. _Net GHG emissions associated with wood-	The cost of this type of siding varies depending on the wood species, but it's generally one of the more	The type of wood that can be used is dependent on the exposure of wood to weather. Wood can also be treated based on the climate of

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
					based houses were 20–50% lower than steel- or concrete-based building systems [28]	expensive options. [55]	area (pressure treat, fire resistant, etc.). [62]
		Fiber cement board/panel	_See Australian Patent No. 515151), metal fibers, glass fibers and other natural and synthetic fibers. _Typical density of building sheets is from about 1.2-1.7 g/cm^3. _Variation in density typically being achievable by compression and dewatering of the fiber cement slurries used in manufacture and by varying the amount of fiber used. [21]	R-Value: 0.37 [27]	IMPACT: _CO_2 emissions and other greenhouse gases are emitted at every stage in the life cycle _Fossil Fuel Depletion [66]	Cost: about $7 to $10 per square foot installed [55]	Weather resistant [63]

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
		Vinyl siding	Polyvinyl Chloride (PVC) is one of the most commonly used thermoplastic polymers in the world (next to only a few more widely used plastics like PET and PP). Rigid PVC is also used in construction as pipe for plumbing and for siding which is commonly referred to by the term “vinyl” in the United States. [14]	R Value (not insulated): 0.61 R Value (1/2" insulation): 1.80 [27]	IMPACT: _Human Toxicity (Emits Air Pollutants) _Global Warming Potential [56]	Life Expectancy: 50 years Due to the nature of the product, this type of siding can range between $1.70 to $4.20 per square foot depending on the brand, color and profile being used. Removal and installation cost is around $40 per hour plus the waste disposal fee. [56]	Vinyl sidings exhibit a high level of water resistance through the field of the wall, effective in climates with high moisture loads. [64]
	Interior Finish	Wood (panel, plywood, OSB)	OSB is manufactured from heat-cured adhesives and rectangular-shaped wood strands that are arranged in cross-oriented layers. Produced in large,	Plywood R Value: 1.25 at 1" thickness Wood Panel R Value: 0.47 at 3/8" [27]	_The GHG benefits of substituting wood for non-wood building materials are generally greater than the energy benefits. _Net GHG emissions associated with wood-based houses were 20–50% lower than	Wood plywood: $1.60-$3.00 (Softwood) Wood plywood: $2.30-$6.00 (Hardwood) [54]	The type of wood that can be used is dependent on the exposure of wood to weather. Wood can also be treated based on the climate of area (pressure treat, fire

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			continuous mats, OSB is a solid-panel product of consistent quality with few voids or gaps. The finished product is an engineered wood panel that shares many of the strength and performance characteristics of plywood. [15]		steel- or concrete-based building systems [28]		resistant, etc.). [62]
		Gypsum board	Gypsum board is often called drywall, wallboard, or plasterboard. It differs from other panel-type building products, such as plywood, hardboard, and fiberboard, because of its noncombustible core and paper facers. [16]	Thermal Conductivity: 0.17 W/(m-K) @ 70 FR Value: 0.45 at 1/2" thickness[29]	IMPACTS:_Emits particulate matter (PM) emissions during manufacturing_May contribute to global warming, acidification, ozone depletion, and abiotic depletion of fossil fuels. [29]	Life Expectancy: 75 years[57]	For installation of gypsum board and finishes, maintain room temperature at not less than 40 degrees F for the mechanical application of gypsum board and not less than 50 degrees for the adhesive application of gypsum board

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
							and for joint treatment, texturing and decoration, unless recommended otherwise by the manufacturer.[16]
Doors & Windows	Exterior doors and windows	Metal	A strong material often used for windows and doors. The sizing of the frame is able to be minimized to maximize glass space. [17]	The estimated energy savings based on the Energy Efficiency Act says that metal-framed windows would reduce energy consumption by 2.2%. [30]	IMPACTS: _Mining that often disrupts soil and natural vegetation _Air emissions (CO, NO_x, O_3) _High energy cost to manufacture BENEFITS: _Recyclable _Long use life [44]	An exterior metal door that is 3' x 7' costs $4000 including installation. [49]	_Steel doors offer good insulation values and do not warp or rot like wood. _Work for places with a lot of moisture. [63]
		Vinyl	A commonly used frame because it has good thermal performance and requires minimal maintenance. It can be made in a cost-effective way. [17]	In comparison to an aluminum framed window with single panes, a double pane window with vinyl frames could save 27-33% of annual heating energy	IMPACTS: _Large source of dioxin-forming chlorine _May need to be disposed of in hazardous waste landfills [45]	Vinyl exterior shutters that are 1' 2" x 4' x7" would cost $130 including installation. [49]	Vinyl can withstand extreme weather conditions including the moisture, heat and cold. [65]

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
				costs. [31]			
		Solid wood	A material used for windows and doors due to its good thermal performance and natural beauty. It requires maintenance such as painting or staining. It can be purchased in many different species. [17]	Requires less energy to make wood doors and window frames Natural honey-combed structure of wood is not thermally conductive [32]	IMPACTS: -Can disrupt ecosystems when harvested -High energy cost to dry out for use -May release harmful organics from resin to seal it BENEFITS: -Can burn whatever isn't used to produce energy -Recyclable [44]	An exterior wood door made of pine that is three feet wide would be about $450 including installation. [49]	Best for a place that does not have a lot of moisture because the wood can warp or rot. [63]
		Single pane	A window/door made up of a single pane of glass. Cheapest option of single/double/triple pane windows. [18]	Single pane windows do work as a barrier, but longwave radiation can increase the heat transport by a factor of 3.1. [33]	IMPACTS: -Needs to be sorted to be reused in new glass containers -Can cause pollution through leaching if used in construction BENEFITS: _Can be recycled and	The lifecycle cost of a single pane window including installing and disposal is roughly $32.37 per square foot. [58]	Single pane windows can be used in warmer climates and get energy savings. [58]

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
					reused in producing new glass containers -Has potential to be used for sub-base material for road pavement construction [46]		
		Double pane	Made up of two panes of glass with a space in the middle that has some gas, such as air, occupying it. [19]	Double pane windows provide a double barrier with air in-between to slow down the heat transfer. Longwave radiation can increase heat transport by a factor of 2.6. [33]	IMPACTS: _Needs to be sorted to be reused in new glass containers _Can cause pollution through leaching if used in construction BENEFITS: _Can be recycled and reused in producing new glass containers _Has potential to be used for sub-base material for road pavement construction [46]	The lifecycle cost of a double pane window including installing and disposing ranges from $19.43 per square foot to $24.48 per square foot. [58]	Double pane windows can be used in warmer climates, but are a necessity in cooler climates to reduce energy loss. [58]

STRUCTURE		MATERIAL	DESCRIPTION	ENERGY EFFICIENCY	ENVIRONMENTAL IMPACTS	LIFE CYCLE COST & COST RELATED INFORMATION	APPROPRIATE USE
		Triple pane	They are made up of three glass panes with two open spaces. The open spaces can be a vacuum, plain air, or another gas. [19]	Triple pane windows provide an extra window and air barrier that can make the energy flows unsteady. Heat loss through windows is heavily based on the number of panes.[34]	IMPACTS: _Needs to be sorted to be reused in new glass containers -Can cause pollution through leaching if used in construction BENEFITS: _Can be recycled and reused in producing new glass containers - Has potential to be used for sub-base material for road pavement construction[46]	The lifecycle cost of a triple pane window including installing and disposing ranges from $48.59 per square foot to $59.24 per square foot.[58]	Triple windows can be used in temperate climates, but they are most beneficial in more extreme climates to reduce energy consumption. [58]
		Window coatings	Either a reflective or clear plastic film that is installed on the inside of the window. They are capable of being installed simply by anyone, so it is not needed to be specially applied. [20]	The cooling required for a building is reduced by 44-56% (depending on the type of film used) due to a reduction in solar transmittance. [35]	IMPACTS: _When burned, may produce poisonous gasses _Buried as a way of getting rid of it BENEFITS: _Can be added to concrete to be recycled [47]	Cost for overhead varies from $9.80 to $13 per square foot. [49]	Places with hot summers and cold winters would benefit from the use of window coatings. [35]

[1] Peri, Traverso, Finkbeiner, & Rizzo. (2012). Embedding "substrate" in environmental assessment of green roofs life cycle: Evidences from an application to the whole chain in a Mediterranean site. Journal of Cleaner Production, 35, 274-287.

[2] Friedberg, A., & O'Brien, J. (2013). Green roof life-cycle assessment: insights from cost-benefit analysis of green roofs versus conventional roofs. Landscape & Irrigation, 37(5), 8+.

[3] Grimmond, C. S. B., Roth, M., Oke, T. R., Au, Y. C., Best, M., Betts, R., … Voogt, J. (2010). Climate and More Sustainable Cities: Climate Information for Improved Planning and Management of Cities (Producers/Capabilities Perspective). Procedia Environmental Sciences, 1, 247–274. https://doi.org/10.1016/j.proenv.2010.09.016

[4] Napolano, L., Menna, C., Asprone, D., Prota, A., & Manfredi, G. (2015). Life cycle environmental impact of different replacement options for a typical old flat roof. The International Journal of Life Cycle Assessment, 20(5), 694-708.

[5] https://www.burlingtonvt.gov/assets/0/122/318/302/614/789/d2107877-d9eb-498b-9389-5672b2194a92.pdf

[6] http://www.doityourself.com/stry/advantages-and-disadvantages-of-a-flat-concrete-roof

[7] Watts, A. (2010). Modern Construction Envelopes (1st Edition. edition). Wien: Springer Vienna Architecture.

[8] North, E. (2011, March 11). What is Fiberglass Insulation? Retrieved March 01, 2017, from http://www.energyauditingblog.com/what-is-fiberglass-insulation/

[9] https://energy.gov/energysaver/insulation-materials

[10] https://energy.ces.ncsu.edu/expanding-foam-defined/

[11] http://ebookcentral.proquest.com.ezproxy.proxy.library.oregonstate.edu/lib/osu/reader.action?docID=727129

[12] http://scholarsmine.mst.edu/cgi/viewcontent.cgi?article=1156&context=bachelors_theses

[13] http://www.understandconstruction.com/wood.html

[14] https://www.creativemechanisms.com/blog/everything-you-need-to-know-about-pvc-plastic

[15] https://www.nachi.org/osb-plywood.htm

[16] https://www.gypsum.org/technical/using-gypsum-board-for-walls-and-ceilings/using-gypsum-board-for-walls-and-ceilings-section-i/

[17] https://windowanddoor.com/article/consumer-info/material-choices-windows-doors

[18] Double Pane vs. Single Pane Windows. (2016, August 02). Retrieved March 11, 2017, from http://www.newmanwindows.com/choosing-double-single-pane-windows/

[19] Triple vs. Double Pane Fiberglass Windows-The Pros and Cons of Double and Triple Glazing Fiberglass Windows. (n.d.). Retrieved March 11, 2017, from http://www.fibertec.com/double-vs-triple-pane-windows/

[20] [38]

[21] Gleeson, J. A., Paradis, K. H., Sloane, B. P., Melmeth, D. L., & Seligman, D. M. (2012). Fiber cement building materials with low density additives. Retrieved from https://www.google.com/patents/CA2402886C?cl=en

[22] https://energy.gov/energysaver/cool-roofs

[23] http://energy.lbl.gov/coolroof/tile.htm

[24] Romes, G. E., Vagades, M. H., & Church, J. T. (1997). Fiberglass spray insulation system and method with reduced density. Google Patents, 1-8. Retrieved 2017, from https://www.google.com/patents/US5641368.

[25] https://www.certainteed.com/resources/SPFALCALongSummary.pdf

[26] http://www.coloradoenergy.org/procorner/stuff/r-values.htm

[27] https://www.archtoolbox.com/materials-systems/thermal-moisture-protection/rvalues.html

[28] "https://www.nrs.fs.fed.us/pubs/jrnl/2008/nrs_2008_upton_001.pdf

http://www.coloradoenergy.org/procorner/stuff/r-values.htm"

[29] "https://fpinnovations.ca/ResearchProgram/environment-sustainability/epd-program/Documents/epd-gypsum.pdf

http://www.engineeringtoolbox.com/thermal-conductivity-d_429.html"

[30] Pape-Salmon, A., & Knowles, W. (2011, January 1). Transforming the window and glazing markets in BC through energy efficiency standards and regulations. Retrieved March 20, 2017, from http://go.galegroup.com.ezproxy.proxy.library.oregonstate.edu/ps/i.do?&id=GALE|A257557811&v=2.1&u=s8405248&it=r&p=PPHI&sw=w&authCount=1

[31] Vinyl window energy and cost savings. (2004, September). Retrieved March 20, 2017, from http://go.galegroup.com.ezproxy.proxy.library.oregonstate.edu/ps/i.do?&id=GALE|A122552883&v=2.1&u=s8405248&it=r&p=PPHI&sw=w&authCount=1

[32] Wood windows and doors increase energy performance. (1993) Retrieved March 30, 2017, from http://bi.galegroup.com.ezproxy.proxy.library.oregonstate.edu/global/article/GALE%7CA19381481/f2c5a71b4485741a39c97263a1b93b94?u=s8405248

[33] Frederick, J. E. (2014). Energy transfer through single- and double-pane windows subject to wintertime environmental radiation. Retrieved March 14, 2017, from http://journals.sagepub.com/doi/pdf/10.1177/1744259113501628

[34] Anci, M., Karabay, H., & Kan, M. (2014). Flow and heat transfer in double, triple and quadruple pane windows. Science Direct. Retrieved 15 March 2017, from http://www.sciencedirect.com/science/article/pii/S0378778814008883

[35] Yin, R., Xu, P., & Shen, P. (2011, November 7). Case study: Energy savings from solar window film in two commercial buildings in Shanghai. Retrieved March 18, 2017, from http://www.sciencedirect.com.ezproxy.proxy.library.oregonstate.edu/science/article/pii/S0378778811005251

[36] https://www.cdc.gov/niosh/docs/2001-110/pdfs/2001-110.pdf

[37] https://www.certainteed.com/resources/CertainTeed_BlowingWool_EPD.pdf

[38] "http://www.iarc.fr/en/media-centre/pr/2001/pr137.html

https://energy.gov/energysaver/types-insulation"

[39] http://eiha.org/media/attach/372/lca_fibre.pdf

[40] http://education.seattlepi.com/environmental-impacts-polyurethane-foam-6242.html

[41] Saadatian, S. S., Freire, F., & Simões, N. (2016). Comparative Life-Cycle Analysis of Insulation Materials in A Dwelling, Addressing Alternative Heating Systems and Life Spans. Journal of Clean Energy Technologies, 4(6), 462–465. https://doi.org/10.18178/JOCET.2016.4.6.333

[42] Flower, D. J. M., & Sanjayan, J. G. (2007). Greenhouse gas emissions due to concrete manufacture. The International Journal of Life Cycle Assessment, 12(5), 282. https://doi.org/10.1065/lca2007.05.327

[43] http://large.stanford.edu/courses/2016/ph240/pourshafeie2/docs/marceau-2007.pdf

[44] Knight, L., Huff, M., Stockhausen, J. I., & Ross, R. J. (2005, June). Comparing energy use and environmental emissions of reinforced wood doors and steel doors. Forest Products Journal, 55(6), 48+. Retrieved from http://go.galegroup.com.ezproxy.proxy.library.oregonstate.edu/ps/i.do?p=AONE&sw=w&u=s8405248&v=2.1&it=r&id=GALE%7CA133644479&asid=152cf0fdd29b7bcaa975d8006058d899

[45] Seewald, N. (2004, December 15). Activist group urges phaseout of PVD. Retrieved March 30, 2017, from http://bi.galegroup.com.ezproxy.proxy.library.oregonstate.edu/global/article/GALE%7CA126585255/1f1ab2e926905845a86dfdd811ccce6b?u=s8405248

[46] Imteaz, M. A., Ali, M. Y., & Arulrajah, A. (2012, May 23). Possible environmental impacts of recycled glass used as a pavement base material. Retrieved March 30, 2017, from http://journals.sagepub.com.ezproxy.proxy.library.oregonstate.edu/doi/abs/10.1177/0734242X12448512

[47] Nikbin, I. M., R, S. R., Allahyari, H., & Fallah, F. (2016, July 10). Feasibility study of waste Poly Ethylene Terephthalate (PET) particles as aggregate replacement for acid erosion of sustainable structural normal and lightweight concrete. Retrieved March 30, 2017, from http://www.sciencedirect.com.ezproxy.proxy.library.oregonstate.edu/science/article/pii/S0959652616300610

[48] Al-Sallal, K. A. (2003). Comparison between polystyrene and fiberglass roof insulation in warm and cold climates. Renewable Energy, 28(4), 603–611.

[49] Plotner, S. C. (2016). Building Construction Cost Data (74th ed.). Rockland, MA: RSMeans.

[50] "http://www.daviddarling.info/encyclopedia/N/AE_natural_fiber_insulation.html

https://www.buildinggreen.com/blog/loose-fill-wool-insulation-oregon-shepherd"

[51] https://www.certainteed.com/resources/SPFALCALongSummary.pdf

[52] https://www.researchgate.net/profile/Janusz_Adamczyk/publication/251576180_Economic_and_environmental_benefits_of_thermal_insulation_of_building_external_walls/links/5647452908aef646e6cf847a.pdf

[5]3 https://www.nrmca.org/research/CIF-Summer-08-Climate.pdf

[54] http://publications.iowa.gov/6278/4/Analyzed_Unit_Cost%2C_Section_4.pdf

[55] https://www.houzz.com/ideabooks/1537973/list/9-top-siding-materials

[56] "https://www.vinylsiding.org/wp-content/uploads/2015/01/Greenpaper.pdf

https://www.thebalance.com/insulated-vinyl-siding-844649"

[57] Scheuer, C., Keoleian, G. A., & Reppe, P. (2003). Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. Energy and Buildings, 35(10), 1049–1064. https://doi.org/10.1016/S0378-7788 (03)00066-5

[58] Minne, E., Wingrove, K., & Crittenden, J. (2015). Influence of climate on the environmental and economic life cycle assessments of window options in the United States. Sciencedirect.com. Retrieved 15 March 2017, from http://www.sciencedirect.com/science/article/pii/S0378778815300141

[59] http://www.homeadvisor.com/cost/insulation/install-blown-in-insulation/#cell

[60] https://www.comfort-now.com/webapp/p/344/types-of-insulation

[61] http://www.understandconstruction.com/walls.html

[62] http://www2.iccsafe.org/states/newjersey/nj_building/PDFs/NJ_Bldg_Chapter23.pdf

[63] Fiberglass, Steel and Wood Comparison. (n.d.). Retrieved April 03, 2017, from https://www.thermatru.com/learn-plan/shopping-tips-tricks/fiberglass-comparison/

[64] https://pdfs.semanticscholar.org/38b2/753f30e3cf79c47dc511a837b80f2be8b10c.pdf

[65] Writer, L. G. (2010, August 13). Advantages of Vinyl Exterior on a House. Retrieved April 03, 2017, from http://homeguides.sfgate.com/advantages-vinyl-exterior-house-8693.html

[66] http://www.ebsbuild.com/wp-content/uploads/pdf/siding/CT-EnvironmentalImpactReport.pdf

APPENDIX D – ALTERNATIVE ENERGY SYSTEMS AND CHARACTERISTICS

Energy Systems	Type	Description	Energy Efficiency	Environmental Impacts	Life Cycle Cost & Related Costs	Appropriate Use
HVAC	VRF	Variable Refrigerant Flow (VRF) systems consist mainly of one outdoor unit and several indoor units. The outdoor unit provides each indoor unit with cooled or heated refrigerant. Using this refrigerant, each indoor unit serves one zone, delivering either heating or cooling. Due to its special configuration, the VRF system can cool some zones and heat other zones, simultaneously. [21]	Energy savings range from 13% to 55% compared to conventional HVAC systems. [21]	BENEFITS: VRF uses R-410a, which is a non-ozone depleting compound. POTENTIAL IMPACTS: R-410a does have a high global warming potential. [6]	For a commercial building (53,608 sq. ft.), assuming a 20-year life (2013 base year): _Initial HVAC system investment: $847,012 ($16,240/ton) _Residual value factor: 0% of initial cost _Energy consumption cost: $63,865/year (Present value: $977,130) _Natural gas cost: $526/year (Present value: $8,864) _Simplified annual OM&R costs: $8,730/year (Present value: $126,091) _Total life cycle cost (Present value: $1,932,666) [21]	Appropriate for Hot and Humid, hot and dry, Warm and humid, warm and dry, mixed climate. Not efficient in very cold regions. In Japan, VRF systems are used in approximately 50% of medium-sized and one-third of large commercial buildings. [32]

	Radiant	Radiant heating and radiant cooling systems are different from typical HVAC systems because they heat or cool surfaces (radiation), rather than the air (convection). Heat is transferred from radiant heating surfaces to other surfaces and people in line-of-sight. Similarly, heat is transferred from warm surfaces and people to radiant cooling panels/slabs to achieve cooling. The surfaces warm or cool the air by convection, as well. [16]	_The heat load and peak load of a radiant heating system were 77% and 80%, respectively, of conventional systems at the same level of thermal comfort, due to increased heat pump efficiency [1]. _By using radiant ceiling panels, which handle part of the sensible thermal load, the volume of supplied air can be reduced, reducing air transport energy by about 20%. This reduces total energy consumption by 10% over a conventional convective system [27]. _By using concrete radiant floors, thermal comfort	BENEFITS: _Radiant floors offer acoustical comfort due to the quiet (non-mechanical) delivery of heat [17] _Radiant heating and cooling systems are often an element of "sustainable" design and are specified in many LEED certified projects. _Utilization of thermal radiation to condition air reduces the dependency on air as the thermal transport mechanism while passing indoor air quality requirements [23]. Thus, allergens (e.g. mold spores, dust, insects, pollens) and disease-causing microorganisms usually carried by the heated air medium can be reduced if not totally avoided.	UAS Residence Hall (Alaska) 25 Study Period (years) 2.90% General Inflation 5.0% Nominal Discount Rate (Dual Fuel/Off-peak Electric Boiler) _Initial Installation Cost (Heating Plant, Hot water System, Controls, Electrical) $580,000 _Maintenance Cost $110,000 _Energy Cost $1,080,000 _Life cycle cost $1,770,000 (Based on 2012 Dollars) [24]	_Radiant cooling is best for dry climates because it can cause condensation in humid air [16] _Radiant systems are not useful for humidity control [16] _Appropriate for buildings, particularly in Arid Southwest [17] _For warehouses which usually have large volume of air, poor insulation, and high infiltration , low and high-intensity Infrared are used [34] _Radiant surface should not be covered with carpet, acoustic panels, or other materials that would insulate them and hamper their effectiveness [34]

			can be enhanced while reducing energy use. Energy savings of up to 60% or more in shops, hangars, and warehouses are possible [17].			

	Wall unit AC	Wall unit HVAC (also known as Wall-mounted unit) incorporates a complete air-cooled refrigeration and air-handling system in an individual pack. It is designed to heat or cool individual room spaces. [47]	Eliminates Duct losses (Duct losses can account for more than 30% of energy consumption for space conditioning) - 30% less cooling cost compared to conventional room AC [37]	BENEFITS: _Ductless systems offer multi-stage filtration that can drastically reduce dust, bacteria, pollen, allergens and other particulates in the air. [38] _Uses R410a refrigerant which is known for its zero ozone depletion potential [20] POTENTIAL IMPACTS: R410a has a high global warming potential (1725 times the effect of carbon dioxide) [20]	Average Life cycle 20 years First Cost : $1,220 PV Energy Cost: $50,380 PV Maintenance: Cost $18,047 Life Cycle Cost : $87,307 (Based on 2010 Dollars) [31]	_Older homes with no ductwork (e.g., radiators or baseboard heat) that never had central air conditioning before. _Additions or outbuildings (e.g., shed, barn, garage) where extending ductwork or cooling/heating capacity is not feasible. _Rooms that are not regularly occupied (indoor unit can be turned off to save money. _Spaces adjacent to unconditioned spaces where ductwork would be exposed to harsher temperatures (e.g., a guest room above a garage). _New construction of homes in areas with high fuel costs. _Older commercial buildings with no existing ductwork for air conditioning or expansions. [38]

	Central Forced Air	Forced air systems use motor-driven blowers to distribute heated, cooled, and otherwise treated air to multiple outlets for the comfort of individuals in confined spaces. [34]	Duct losses in Central Forced air AC can account for more than 30% of energy consumption for space conditioning, especially if the ducts are in an unconditioned space such as an attic. [37]	POTENTIAL IMPACTS: _Without regular furnace filter maintenance, system could spread the kind of airborne particles it meant to filter out. _Each time the system cycles on, the fans turning and air being pushed through the vents produces noise. _In humid climates, high indoor humidity is one of the most serious comfort problems during the cooling season. Often made worse by leaky ducts, high humidity can result in mold growth, mildew, and wood rot. In addition to damaging the appearance or the structural integrity of the building, these organisms can affect the health of the occupants if they	55,000 square foot floor area (for a 3-story hospital in Texas) - Cost per square foot $150.70. Initial Investment Cost - $739,000. Residual Value (5%)-$ 37,000 Annual Fuel/Electric Cost - 4432,500 Annual Sustainment - $25,500 Discount factor (3%). NPV of HVAC Life cycle cost ($ 410,431,100) -Based on 2004 Dollars [26]	Most Commonly Installed in North America (Very Popular in USA) [39]

				become airborne. [36]		

	Gas Heater Unit	_A gas unit heater is a space heater used to heat a room or outdoor area by burning natural gas, liquefied petroleum gas, propane or butane. Natural gas is combusted and exhaust gases are piped through a heat exchanger before exiting through a flue. Fan circulates air across the heat exchanger, warming the space. _Gas heater is a generic term referring to several categories of non-centralized heating equipment. Within this categorization, indirect-fired, non-condensing unit heaters represent the baseline technology with	_Efficiency ranges from 78 to 93% (Depends on Vent system. High efficiency for pulse combustion). _Off-cycle losses through the vent flue represent the primary parasitic loss for gravity vented units, reducing their seasonal efficiencies from 80-83% to 62-64%. [11]	BENEFITS: _Burning natural gas for energy results in fewer emissions of nearly all types of air pollutants and carbon dioxide (CO_2) per unit of heat produced Compared to coal or refined petroleum product. _DOE analysis indicates that every 10,000 U.S. homes powered with natural gas instead of coal avoids the annual emissions of 1,900 tons of NO_x, 3,900 tons of SO_2, and 5,200 tons of particulates [45]. POTENTIAL IMPACTS: _Methane is the primary component of natural gas which is a potent greenhouse gas (34 times stronger than CO_2 at trapping heat over a 100-year	Power Vent - 400,000 BTU, 115 Volt Initial cost: $ 2,074.95, 83% efficiency. Life cycle approximately 20 years. [14]	Unit heaters are a major source of energy use in USA, accounting for nearly 18% of primary space heating energy use for commercial buildings, and most prominently appear in warehouses, distribution centers, loading docks, etc. [7]

		several options representing higher efficiency technologies. [33]		period and 86 times stronger over 20 years) [8].		

Boiler	**Condensing**	Condensing boilers are water heaters fueled by gas or oil. Condensing boilers achieve high efficiencies because they can recapture the latent energy from the moisture in the combustion gases when those gases condense. For condensing to occur, the boiler's heat exchanger surface temperature must be below the flue gas dew point. If the return water temperature is low enough, it will cool the heat exchanger below the dew point and the gases will condense. Therefore, strategies that lower the return	Condensing boiler efficiency can theoretically reach 88-98% at full condensation (80% from fuel being burned and 8-18% from steam condensation). Efficiency improvement is in order of 10-15 % compared to conventional boilers. [40]	BENEFITS: Depending on the system replaced and the type fuel used, condensing boilers can reduce GHG, NO_x, PM and CO emissions substantially, especially compared with conventional (non-condensing) boilers and even more compared to electric heating systems. [13]	The example analyzes condensing boiler system, in a building with heating available on demand continuously, 7 days a week, for a 39-week heating season. Costs are based on a 25-year life and have included an inflationary rate of 2% (3* Purewell VariHeat 95kW condensing boilers). _New boilers+ Commissioning: $15,572.92. _Energy Cost: $493,044 for gas and $1,532 for electricity. _Whole life cycle cost: $547,071. [5]	Condensing boilers are now largely replacing earlier, conventional designs in powering domestic central heating systems in Europe and, to a lesser degree, in North America. In the United States, there is a Federal tax credit for the installation of condensing boilers and additional rebates from power companies in some states. In Western Canada, energy suppliers now offer energy rebates when these systems are installed in multi-unit dwellings. The decrease in natural gas prices in North America has resulted in increased retrofitting of existing boiler installations with condensing equipment. [40]

		water temperature will improve the boiler's efficiency. [44]				
Lighting	**FL**	Fluorescent lamps use electric current conducted through inert gas which produces UV light which is ultimately converted to white visible light after interacting with phosphors. [48]	Fluorescent lamps use 25%-35% of the energy used by incandescent products to provide a similar amount of light. They also last about 10 times longer (7,000-24,000 hours). [56]	IMPACTS: Release of mercury into water, air, and soil. CO_2 emissions Contain heavy metals [19]	_Lifespan of 24,000–80,000 hours _30 to 80 lumens per watt efficacy [48], [62]	Industrial and commercial lighting, residential lighting, and street and outdoor lighting are all candidates for LEDs. [64]

	LED	Light emitting diodes, or LEDs, are a type of solid state lighting which converts electricity into light using semiconductors. [49]	LEDs use only 20%–25% of the energy and last up to 25 times longer than the traditional incandescent bulbs they replace. LEDs use 25%–30% of the energy and last 8 to 25 times longer than halogen incandescent. LEDs use 83% of the energy and last 2.5 times longer than compact fluorescent lamps. [49], [58]	IMPACTS: CO_2 emissions BENEFITS: Less greenhouse gases when compared to FL or HPS [19]	_Lifespan of 30,000 to 50,000 hours _Approximately $1/klm _160 to 170 lumens per watt efficacy [48], [62], [69]	Industrial, commercial, outdoor, warehouse, and garage lighting are all ideal candidates for LED lighting. Any application where lighting with a high color rendering index is suitable. [65]

	High Pressure Sodium	High pressure sodium (HPS) lighting is a long lasting and efficient high intensity discharge lighting that is typically only used for lighting outdoor areas, parking garages, or other industrial applications due to the poor color rendering light produced. [50]	Use 1.35 times as much energy and lasts 0.48 times as long when compared to LED. [59]	IMPACTS: High Acidification, Global Warming, Eutrophication, and Human Toxic Potentials BENEFITS: Low terrestrial eco-toxicity potential impacts [9]	-Lifespan of 16,000 to 40,000 hours -70 to 130 lumens per watt efficacy	Due to low color rendition, HPS lighting is best used for street and outdoor area lighting, parking garages, and some industrial applications. However, LEDs are still typically recommended over HPS.

Solar PV		[51]	Solar energy can be used to effectively power a variety of energy consuming building systems. Depending on size and intermittence of the solar power system installed, the cost of utilities, such as electricity and natural gas, can be effectively reduced or eliminated. [68]	BENEFITS: _Reduction in CO_2, NO_x, SO_2, and particulates. [68]	At efficiencies ranging from 15-20%, the cost of a module is $300/m^2. Accompanying fixed costs include the inverter, grid connection, etc., which increase the total installed system cost by a factor of ~2.	Weather and Climate affect solar thermal system efficiency. Geographic locations further from the equator experience a seasonal reduction in solar radiation availability. Local climate can significantly affect the power output of solar thermal arrays. During the winter, the sun sits lower in the sky increasing the amount of atmosphere light must pass through thus decreasing the light intensity. Additionally, locations with cloudy, rainy, or snowy conditions for large portions of the year may encounter significant power decreases. [66]

Solar Thermal		Solar thermal heating is a proven technology that harnesses solar radiation from the sun to heat water in place of conventional methods. [51]	Solar energy can be used to effectively power all systems in the building. Depending on size and intermittence of the solar power system installed, the cost of utilities such as electricity and natural gas costs can be effectively reduced or eliminated. [68]	BENEFITS: _Reduction in CO_2, NO_x, SO_2, and particulates. [68]	The cost of solar thermal systems varies based on site location and usage. Typical installation cost is $15,000 for a small commercial heating system, which includes solar collectors, water tanks, and other auxiliary components (pipes, pumps, valves, plumbing, wiring, etc.). [63]	Weather and Climate affect solar thermal system efficiency. Geographic locations further from the equator experience a seasonal reduction in solar radiation availability. Local climate can significantly affect the power output of solar thermal arrays. During the winter, the sun sits lower in the sky increasing the amount of atmosphere light must pass through thus decreasing the light intensity. Additionally, locations with cloudy, rainy, or snowy conditions for large portions of the year may encounter significant power decreases. [66]

Geothermal	**Geothermal heat pumps or ground-source heat pumps**	Geothermal heat pumps (GHPs), sometimes referred to as GeoExchange, earth-coupled, ground-source, or water-source heat pumps, use the constant temperature of the earth as the exchange medium instead of the outside air temperature. As with any heat pump, geothermal and water-source heat pumps can heat, cool, and, if so equipped, supply a building with hot water. [52]	Geothermal heat pumps can save energy costs in heating and cooling applications by eliminating electricity- or natural gas-based heating and cooling. [28]	Benefits _Reduction in CO_2, NO_x, SO_x when replacing electric and natural gas heating and cooling systems Potential impacts _Surface water pollution _Underground water pollution _Ecosystems quality _Human health (human toxicity) _Metal depletion _Ozone depletion [12]	The average cost of geothermal heat pumps ranges from $9-$12 per sq. ft. of building area. Installation costs include drilling, piping, plumbing, etc. [15]	Below the Earth's surface, the ground remains at a relatively constant temperature. Depending on latitude, ground temperatures range from 45°F (7°C) to 75°F (21°C). This ground temperature is warmer than the air above it during the winter and cooler than the air in the summer. The geothermal heat pump takes advantage of this by exchanging heat with the earth through a ground heat exchanger. [52]

Wind		Wind is created by the unequal heating of the Earth's surface by the sun. Wind turbines cleanly convert the kinetic energy in wind into electricity. When the wind spins the wind turbine's blades, a rotor captures the kinetic energy of the wind and converts it into rotary motion to drive a generator. [53]	Small wind electric systems can: Lower electricity bills by 50%–90%. Help avoid the high costs of having utility power lines extended to a remote location. Help uninterruptible power supplies ride through extended utility outages. [53]	BENEFITS: _92% lower global warming potential than grid electricity _26% lower terrestrial ecotoxicity. POTENTIAL IMPACTS: _Depletion of abiotic elements _Increased fresh water and human toxicity _Depletion of fossil resources [30]	A 2-MW wind turbine with 35% utilization capacity will provide 0.5-0.7 years payback on energy. Onshore small wind turbine costs span from $3/watt to $7/watt. [29]	Rural settings, open landscape with relatively undisturbed airflow and modest average wind speeds of 4–6 m/s. In the built environment, average wind speeds are generally low, around 2–4 m/s, because buildings tend to shelter installations and slow down wind. [3]

Biomass		Small modular biomass systems can help supply distributed, on-site electric power for rural areas and businesses. These systems use locally available biomass fuels such as wood, crop waste, animal manures, and landfill gas. Small systems rated at 5 MW down to 5 kW can provide heat and power when and where needed. [54]	Specific benefits depend upon the intended use and fuel source, but often include: greenhouse gas and other air pollutant reductions, energy cost savings, local economic development, waste reduction, and the security of a domestic fuel supply. In addition, biomass is more flexible (e.g., can generate both power and heat) and reliable (as a non-intermittent resource) energy option than many other sources of renewable energy. [4]	BENEFITS: _Carbon neutral POTENTIAL IMPACTS: _global warming potential due to high nitrogen production in biomass farms _Soil erosion _Loss of water holding capacity of soil, soil biota, soil organic matter, and soil micronutrients _Land degradation [46]	_Collection: typically, $5 to $7/ton. _Resources cost: farmer premiums of up to $15/ton for haul distances within 15 miles or $7/ton or less for distances around 50 miles. _Transportation: $7 to $10/dry ton for conventional bales, $4 to $7/dry ton for compacted bales. For wood feedstocks, costs between $8 and $15/ton. _Storage: Enclosed structure with crushed rock floor ($10 to $15/ton), open structure with crushed rock floor ($6 to $8/ton), reusable tarp on crushed rock ($3/ton), outside unprotected on crushed rock ($1/ton), and outside unprotected on ground ($0/ton) [4]	Climate affects biomass feedstock production. Similar to any other agricultural product, climate and weather significantly impact feedstock production throughput and storage. [46]

Diesel Generator		A diesel generator combines a diesel engine and an electric generator. It is designed to run on fuel oils, but can be modified to run on other fuels such as natural gas. [55]	Diesel generators have a conversion efficiency up to 50%. They ensure good power quality and the fuel is easy to use. [60]	IMPACTS: _Air pollution _Water pollution _High global warming potential due to diesel emissions _Human health impact due to diesel emissions _Climate change [43]	The annualized cost of ownership diesel generators depends on the number of hours of use (for 8 hours: $4500, for 52 hours: $4900, for 72 hours: $4900, and for 176 hours: $5300). The diesel generator is one of the lower-cost power options, but this technology has some challenges due to the cost of annual maintenance requirements and attributes not captured in the cost of ownership, such as noise and emissions. [25]	Local conditions (altitude, temperature and humidity) are crucial for proper ignition and functioning of a generator. All generators, irrespective of the fuel that powers them, require adequate air for combustion. Decreased air levels can lead to startup failure in diesel engines. When air and fuel are infused together, the compressed air becomes hot and when peak temperature and pressure is achieved, diesel is injected, which then ignites under the given conditions. [67]

[1] Zmeureanu, R., Fazio, P.P., and Haghighat, F. (1988). Thermal Performance of Radiant Heating Panels. T ASHRAE,13-27.

[2] Zabalza Bribián, I., Aranda Usón, A., & Scarpellini, S. (2009). Life cycle assessment in buildings: State Of-the-art and simplified LCA methodology as a complement for building certification. Building and Environment, 44(12), 2510–2520. http://doi.org/10.1016/j.buildenv.2009.05.001

[3] Wood, D. (2011). Small wind turbines. In Advances in wind energy conversion technology (pp. 195-211). Springer Berlin Heidelberg.

[4] Wickwire, S. (2007). Biomass Combined Heat and Power catalog of technologies. Washington, DC.

[5] Whole life costs of a commercial heating system. (2017). www.hamworthy-heating.com. Retrieved 13 March 2017, from https://www.hamworthy-heating.com/boiler-best-practice/lifecycle-costs-of-heating-system

[6] Variable refrigerant flow (VRF) | Seventhwave. (2017). Seventhwave.org. Retrieved 2 March 2017, from http://www.seventhwave.org/new-technologies/variable-refrigerant-flow-vrf

[7] U.S. Department of Energy, (2002). DOE Unit Heater Spreadsheet.

[8] Tollefson, J. (2013). Methane leaks erode green credentials of natural gas. Retrieved 15 March 2017, from

[9] Tähkämö, L., & Halonen, L. (2015). Life cycle assessment of road lighting luminaires – Comparison of light-emitting diode and high-pressure sodium technologies. Journal of Cleaner Production, 93, 234-242. doi:10.1016/j.jclepro.2015.01.025

[10] Saner, D., Juraske, R., Kübert, M., Blum, P., Hellweg, S., & Bayer, P. (2010). Is it only CO_2 that matters? A life cycle perspective on shallow geothermal systems. Renewable and Sustainable Energy Reviews, 14(7), 1798-1813.

[11] Sachs, H. (2003). Unit Heaters Deserve Attention for Commercial Programs. ACCEEE.

[12] Rybach, L. (2003). Geothermal energy: sustainability and the environment. Geothermics, 32(4), 463-470.

[13] Rural Energy - Condensing boilers for home heating. (2017). Rural-energy.eu. Retrieved 13 March 2017, from http://www.rural-energy.eu/solutions/7/366/Condensing-boilers-for-home-heating#.WMBYM1XytaQ

[14] Reznor UDAP-400 Power Vented Gas Fired Unit Heater, NG, Aluminized Heat Exchanger - 400,000 BTU. (2017). eComfort. Retrieved 23 March 2017, from https://www.ecomfort.com/Reznor-UDAP-400/p46964.html

[15] Rafferty, K. (1995). A capital cost comparison of commercial ground-source heat pump systems (No. CONF-950624--). American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta, GA (United States).

[16] Radiant Heating and Cooling | Sustainability Workshop. (2017). Sustainabilityworkshop.autodesk.com. Retrieved 10 March 2017, from https://sustainabilityworkshop.autodesk.com/buildings/radiant-heating-and-cooling

[17] Radiant Floors for heating and cooling - Energy Efficient Building - Concrete Radiant Floor. (2017). Concretethinker.com. Retrieved 10 March 2017, from http://www.concretethinker.com/applications/Radiant-Floors.aspx

[18] Radiant Cooling | Department of Energy. (2017). Energy.gov. Retrieved 9 March 2017, from https://energy.gov/energysaver/radiant-cooling

[19] Principi, P., & Fioretti, R. (2014). A comparative life cycle assessment of luminaires for general lighting for the office – compact fluorescent (CFL) vs Light Emitting Diode (LED) – a case study. Journal of Cleaner Production, 83, 96-107. doi:10.1016/j.jclepro.2014.07.031

[20] Prah, F. (2001). REFRIGERANT 410A. Refrigeration Service Engineers Society. Retrieved from https://www.rses.org/assets/r410a/R-410A.PDF

[21] Park, J. (2013). Comparative Analysis of the VRF system and Conventional HVAC system, focused on life cycle cost (Master of Science). Georgia Institute of Technology: School of Architecture.

[22] Navigant Consulting, Inc,. (2014). Field Demonstration of High-Efficiency Gas Heaters. Retrieved from https://energy.gov/sites/prod/files/2014/11/f19/gas_heater_demo_report.pdf

[23] Miriel, J., Serres, L., & Trombe, A. (2002). Radiant ceiling panel heating–cooling systems: experimental and simulated study of the performances, thermal comfort and energy consumptions. Applied Thermal Engineering, 22(16), 1861-1873. http://dx.doi.org/10.1016/s1359-4311 (02)00087-x

[24] Life Cycle Cost Analysis-UAS Student Residence Hall. (2012). Retrieved 17 March 2017, from https://www.uas.alaska.edu/facilities_services/docs/fpc/residencehalllifecyclecostanalysis.pdf

[25] Kurtz, J., Saur, G., Sprik, S., & Ainscough, C. (2014). Backup power cost of ownership analysis and incumbent technology comparison. National Renewable Energy Laboratory.

[26] Krus, C. (2004). Analysis of Life Cycle Cost Methods for Heating, Ventilation, and Air Conditioning Systems in Hospitals (M.S). University of Texas, Austin.

[27] Imanari, T., Omori, T., & Bogaki, K. (1999). Thermal comfort and energy consumption of the radiant ceiling panel system. Energy and Buildings, 30(2), 167-175. http://dx.doi.org/10.1016/s0378-7788 (98)00084-x

[28] Hepbasli, A., & Akdemir, O. (2004). Energy and exergy analysis of a ground source (geothermal) heat pump system. Energy conversion and management, 45(5), 737-753.

[29] Haapala, K. R., & Prempreeda, P. (2014). Comparative life cycle assessment of 2.0 MW wind turbines. International Journal of Sustainable Manufacturing, 3(2), 170-185.

[30] Greening, B., & Azapagic, A. (2013). Environmental impacts of micro-wind turbines and their potential to contribute to UK climate change targets. Energy, 59, 454-466.

[31] GREEN BUILDING CERTIFICATION SYSTEMS AND RESOURCES (1st ed., pp. 135-224). Retrieved from http://www.fldoe.org/core/fileparse.php/5599/urlt/0074676-lccgmbsfpef-2.pdf

[32] Goetzler, W. (2007). Variable Refrigerant Flow Systems. American Society of Heating, Refrigerating and Air-Conditioning Engineers, 24-31.

[33] Gas heaters. (2017). En.wikipedia.org. Retrieved 17 March 2017, from https://en.wikipedia.org/wiki/Gas_heater

[34] Fundamentals of HVAC Systems | ashrae.org. (2017). Ashrae.org. Retrieved 8 March 2017, from https://www.ashrae.org/education--certification/self-directed-or-group-learning/fundamentals-of-hvac-systems

[36] Forced Air Systems - Everything You Need to Know. (2017). HVAC.com. Retrieved 10 March 2017, from https://www.hvac.com/blog/what-are-forced-air-systems-here-are-3-things-you-should-know

[37] Ductless Mini-Split Air Conditioners | Department of Energy. (2017). Energy.gov. Retrieved 17 March 2017, from https://energy.gov/energysaver/ductless-mini-split-air-conditioners

[38] Ductless Heating & Cooling | Mini Split Systems | ENERGY STAR. (2017). Energystar.gov. Retrieved 17 March 2017, from https://www.energystar.gov/products/heating_cooling/ductless_heating_cooling

[39] Culberson, A. (2017). Forced Air Heating: What Makes It So Popular in the U.S.? Geisel Heating, Air Conditioning and Plumbing. Retrieved 10 March 2017, from http://blog.gogeisel.com/2014/02/25/forced-air-heating/

[40] Condensing Boilers. (2014). Gsa.gov. Retrieved 30 March 2017, from https://www.gsa.gov/portal/mediaId/196871/fileName/GPG_Findings_04_-_Condensing_Boilers.action

[41] Condensing Boilers Evaluation: Retrofit and New Construction Applications. (2014). Retrieved 13 March 2017, from https://www.gsa.gov/portal/mediaId/197387/fileName/GPG_Condensing_Boilers_NREL_06-2014.action

[42] Bhat, I. K., & Prakash, R. (2009). LCA of renewable energy for electricity generation systems—a review. Renewable and Sustainable Energy Reviews, 13(5), 1067-1073.

[43] Awofeso, N. (2011). Generator diesel exhaust: a major hazard to health and the environment in Nigeria. American journal of respiratory and critical care medicine, 183(10), 1437-1437.

[44] Arena, L. (2013). Measure Guideline: Condensing Boilers— Control Strategies for Optimizing Performance and Comfort in Residential Applications. Retrieved from http://www.nrel.gov/docs/fy13osti/57826.pdf

[45] Alvarez, R., Pacala, S., Winebrake, J., Chameides, W., & Hamburg, S. (2012). Greater focus needed on methane leakage from natural gas infrastructure. Proceedings of the National Academy of Sciences, 109(17), 6435-6440. http://dx.doi.org/10.1073/pnas.1202407109

[46] Abbasi, T., & Abbasi, S. A. (2010). Biomass energy and the environmental impacts associated with its production and utilization. Renewable and Sustainable Energy Reviews, 14(3), 919-937.

[47] 2016 ASHRAE handbook: HVAC Systems and Equipment (IP Ed.). Atlanta, GA: American Society of Heating, Refrigeration, and Air-Conditioning Engineers.

[48] https://energy.gov/eere/energybasics/articles/fluorescent-lighting-basics

[49] https://energy.gov/energysaver/lighting-choices-save-you-money

[50] https://energy.gov/eere/energybasics/articles/high-intensity-discharge-lighting-basics#hpsl

[51] World Energy Outlook 2004 (International Energy Agency, Paris, 2004), www.worldenergyoutlook.org/.

[52] https://energy.gov/energysaver/geothermal-heat-pumps

[53] https://energy.gov/energysaver/small-wind-electric-systems

[54] http://www.nrel.gov/docs/fy03osti/33257.pdf

[55] https://en.wikipedia.org/wiki/Diesel_generator

[56] https://energy.gov/energysaver/fluorescent-lighting

[57] https://energy.gov/energysaver/lighting-choices-save-you-money

[58] https://energy.gov/energysaver/how-energy-efficient-light-bulbs-compare-traditional-incandescents

[59] https://energy.gov/sites/prod/files/2014/01/f7/led_parking_lights_navfac.pdf

[60] https://www.slideshare.net/eecfncci/energy-efficiency-in-diesel

[61] https://energy.gov/eere/energybasics/articles/lighting-basics

[62] https://www.dmme.virginia.gov/DE/LinkDocuments/HandbookLighting.pdf

[63] http://www.dovetailsolar.com/getattachment/Solar-Thermal/Pricing-for-Solar-Heating-Systems/Commercial-SOLAR-THERMAL-Price-Sheet.pdf.aspx

[64] https://energy.gov/energysaver/led-lighting

[65] https://energy.gov/sites/prod/files/2015/07/f24/led-adoption-report_2015.pdf

[66] H Aberlin, Heinrich, and Herbert Eppel. Photovoltaics. Wiley, 2012.

[67] http://www.dieselserviceandsupply.com/Generator_Output_Rating.aspx

[68] Turner, John A. "A realizable renewable energy future." Science 285.5428 (1999): 687-689.

[69] https://www.energy.gov/sites/prod/files/2016/10/f33/Efficacy%20White%20Paper%20Oct%202016.pdf