

## **ABSTRACT**

MUELLER, KATELYN ELIZABETH. Using Life Cycle Assessment and Environmental Payback Period to Evaluate Commercial Building Replacement. (Under the direction of Drs. Joseph DeCarolis and Jeremiah Johnson).

As environmental and human health impacts garner more global concern, buildings represent near-term opportunities to mitigate impacts cost-effectively. Environmental payback period (EPP) is an existing metric that applies the concept of economic payback period to environmental impacts. This project investigates the application of an EPP methodology to commercial buildings to make recommendations regarding building replacement, informing the point at which existing, underperforming buildings should be replaced with new, high-performing ones.

The EPP estimation model developed in this work includes the application of life cycle assessment (LCA) to generate an emissions inventory that includes building construction and operation. The inventory is used to calculate environmental impacts, which are in turn used to estimate the EPP by impact category. The model is capable of applying variations in discount rate and energy efficiency. While global warming potential is frequently used as the benchmark for the environmental performance of buildings, this project also seeks to determine if other, often unassessed impact categories may be areas of concern for building projects, indicated by high EPPs. The selected case study is a college administrative building.

Findings indicate that it is environmentally advantageous to replace an existing building when the new building produces high energy savings when compared to the existing building, and when environmental impacts are evaluated using a low discount rate. Additionally, displacement of dirtier fuels when constructing a more energy efficient building further improves EPP. All ten impacts from the EPA TRACI impact assessment methodology are

evaluated, and the sensitivity of each impact to building-related changes vary. A key indicator of sensitivity to energy reduction and discount rate is the ratio of initial construction impacts to annual operational savings. Impacts with higher ratios are more sensitive to changes, while lower ratios are less sensitive. EPP values range widely (i.e., less than a decade to over a century) by both impact category and specified parameters, but base case conditions estimate EPP at between 7 and 50 years. Thus, the time horizon and targeted impacts for reduction will govern whether or not building replacement is truly advantageous for the entity considering the project.

© Copyright 2018 by Katelyn Elizabeth Mueller  
All Rights Reserved

Using Life Cycle Assessment and Environmental Payback Period to  
Evaluate Commercial Building Replacement

by  
Katelyn Elizabeth Mueller

A thesis submitted to the Graduate Faculty of  
North Carolina State University  
in partial fulfillment of the  
requirements for the degree of  
Master of Science

Civil Engineering

Raleigh, North Carolina

2018

APPROVED BY:

---

Dr. Joseph DeCarolus  
Committee Co-Chair

---

Dr. Jeremiah Johnson  
Committee Co-Chair

---

Dr. Ranji Ranjithan

## **DEDICATION**

To the Bobbi Gibbs and Kathrine Switzers of the engineering profession.

## **BIOGRAPHY**

Katelyn Mueller was born in Wilmington, NC in 1994. She is the eldest child of Peter and Suzanne Mueller, with younger brothers Matthew and Alexander. Having lived in five states as a child, her earliest memory is of a tornado in Ft. Leavenworth, Kansas, but other formative experiences include a smattering of broken bones, stitches, rec sports, and countless visits to national parks and historic sites. Upon graduating from Robinson Secondary School in Fairfax, Virginia in 2012, she enrolled at North Carolina State University.

Coming from a long line of civil engineers and surveyors, Katelyn did her best to avoid the family trade, yet completed her Bachelor of Science in Civil Engineering and the University Honors Program at NC State in 2016. She decided to continue her education by pursuing a master's degree through which she could further explore the environmental implications of the built environment.

In addition to the completion of this thesis, Katelyn's other notable graduate school achievements include a third-place finish in the annual Krispy Kreme Challenge, the successful completion of the (only slightly more prestigious) Boston Marathon, and a highly sought-after first-place trivia finish as a member of team "Science is a Hoax".

## ACKNOWLEDGMENTS

I would first like to acknowledge my advisor, Dr. Joe DeCarolis, for the instrumental role he played in the completion of this thesis. I am truly grateful for his support and guidance throughout this process, beginning with his willingness to help me develop and pursue a project of my own interest. As I entered graduate school I was aware of my passions, yet had only a foggy vision of what I ultimately wanted from a career. Thank you for taking the time to help me examine potential pathways, and for assisting me in pursuing opportunities as I came upon them throughout my graduate program.

Additional thanks to Dr. Jeremiah Johnson for his willingness to join my committee midway through this project, shortly after arriving at NC State. I greatly appreciate all of your valuable insights and suggestions. I would also like to acknowledge Dr. Ranji Ranjithan for both serving on my committee and cultivating my appreciation for challenging problems with an array of viable solutions.

Many thanks to John Majernik at Wake Tech Community College and Candis Parker at Balfour Beatty Construction for their interest in this project and providing the data that made it possible.

There are numerous others without whom the completion of this thesis – at least a remotely graceful completion of this thesis – would not have been possible:

To each of my running friends: thank you for the countless miles you logged alongside me, many of which were accompanied by monologues about spreadsheets, graphs, and writing. Thank you for your company, for your patience, and for running fast enough to make me shut my mouth from time to time.

To my Fellowship Raleigh Church family: thank you for your care and support, and for serving as a lay-audience as I practiced presenting and communicating my research.

To my parents, brothers, and extended family: thank you for encouraging me to take on new challenges, for celebrating the milestones with me, and for never failing to communicate to me that you are proud of my efforts and accomplishments. I love you all and am fortunate to have such great examples in my life.

To Hannah Field: thank you for your friendship, and for being an incredible example of how to support and encourage others – both in person and from a number of states away.

To my friends and compatriots in Mann Hall, particularly those on the fourth floor: thank you for the laughs, the trivia victories, and for being a light in our shared windowless box.

Lastly, to Drs. Brina Montoya and Emily Berglund, without whom I may not have opted to pursue graduate school: thank you both for your early encouragement and for helping me recognize my potential as a student, researcher, and future professional.

## TABLE OF CONTENTS

LIST OF TABLES .....	vii
LIST OF FIGURES .....	viii
1 INTRODUCTION .....	1
2 MATERIALS AND METHODS.....	6
2.1 Existing Tools and Techniques.....	6
2.1.1 Life Cycle Assessment .....	6
2.1.2 Payback Period .....	7
2.1.3 Environmental Payback Period .....	8
2.2 EPP Framework and Case Study .....	10
2.2.1 LCA Application .....	11
2.2.2 Case Study .....	13
2.2.3 Model Structure & Data .....	13
2.2.4 Base Comparison.....	16
2.2.5 Energy Reduction .....	17
2.2.6 Discount Rate .....	17
2.2.7 Variation in Material Selection.....	18
2.2.8 Variation in Electricity Supply .....	18
2.2.9 Building Efficiency.....	21
2.2.10 Spreadsheet Function.....	22
3 RESULTS AND DISCUSSION .....	24
3.1 Base Comparison .....	24
3.2 Energy Reduction.....	26
3.3 Discount Rate.....	28
3.4 Interaction of Energy Reduction and Discount Rate .....	31
3.5 Variation in Material Selection.....	33
3.6 Variation in Electricity Supply .....	34
3.7 Building Efficiency.....	37
4 IMPLICATIONS .....	39
4.1 Green Building Rating Context .....	39
4.2 Shortcomings of EPP .....	40
4.3 Comparison to Existing Literature.....	41
4.4 Other Temporal and Discount Rate Considerations .....	43
5 FUTURE WORK.....	45

5.1	Role of Demolition and Recycling Methods .....	45
5.2	Consideration of Renovation and New Construction .....	47
5.3	Changes to Annual Energy Reduction .....	49
6	CONCLUSION.....	49
	REFERENCES .....	51
	APPENDIX.....	56
	Appendix A1 New Building Materials .....	57
	Appendix A2 Energy Consumption Data .....	58
	Appendix A3 AEO 2017 SERC Fuel Mix Data .....	60

## LIST OF TABLES

Table 1.	Differences in impacts per kWh for manual and Ecoinvent SERC representations .....	20
Table 2.	Impact ratios for 25% energy reduction and 0% discount rate.....	30
Table 3.	Percent change in EPP due to 25% decrease in material input.....	33
Table A1.	Materials included in representation of new building construction.....	57
Table A2.	Existing building annual electricity use .....	58
Table A3.	Existing building annual fuel oil use .....	58
Table A4.	New building monthly electricity use .....	58
Table A5.	Projected generation contributions by fuel type for SERC - AEO 2017 Reference .....	60
Table A6.	Projected generation contributions by fuel type for SERC - AEO 2017 Reference with CPP .....	60

## LIST OF FIGURES

Figure 1.	LCA framework diagram.....	7
Figure 2.	Graphical representation of environmental payback period (EPP) applied to buildings.....	9
Figure 3.	Environmental payback period (EPP) model workflow. ....	10
Figure 4.	System boundary diagrams for existing and new buildings. ....	12
Figure 5.	Base case environmental payback periods, normalized impacts from initial construction, and normalized 50 year cumulative impact savings. ....	25
Figure 6.	Percent energy reduction versus environmental payback period for TRACI impact categories. . ....	27
Figure 7.	Percent discount rate versus environmental payback period for TRACI impact categories.. ....	29
Figure 8.	Environmental payback period and normalized 50 year cumulative impact savings when percent energy reduction and discount rate are varied simultaneously.. ....	32
Figure 9.	Effect of grid transition over time on environmental payback period. ....	35
Figure 10.	Effect of 100% solar electricity supply on environmental payback period when applied to just the new building and to both buildings. ....	36
Figure 11.	Comparison of changes to energy efficiency required to eliminate payback for specified impact categories, assuming 0% discount rate and an initial energy reduction of 25% between buildings.....	37

# 1 INTRODUCTION

As population increases, new building construction along with building renovation and replacement is necessary to accommodate growth. The construction, demolition, and operation of buildings produce a range of environmental impacts. In 2017, residential and commercial buildings accounted for 39% of final U.S. energy consumption, or approximately 29 quadrillion BTU (EIA, 2018). Building-related energy consumption corresponds to a number of upstream environmental impacts, including greenhouse gas emissions that contribute to climate change. In addition, construction generates a large material burden as included building elements must be manufactured, using both energy and material resources (Kofoworola & Gheewala, 2008; J. Peng, Lu, & Yang, 2013; Scheuer, Keoleian, & Reppe, 2003; Thiel et al., 2013; Vandenbroucke, Galle, De Temmerman, Debacker, & Paduart, 2015).

Increased energy and resource efficiency in buildings offer economic savings in the operations phase and a motivation for pursuing performance improvements. As environmental and human health impacts garner more global concern, buildings represent near-term opportunities to mitigate impacts cost-effectively, and industry has begun to pivot toward high performance buildings. Language outlined in the Energy Policy Act of 2005 passed by the U.S. Congress defines high performance buildings as buildings that optimize “energy efficiency, durability, life-cycle performance, and occupant productivity” (National Institute of Building Sciences, 2017). Thus, high performance building design considers both physical building performance and occupant well-being. High performance buildings are often considered synonymous with “green buildings”, which are designed to incorporate both healthier and more resource-efficient practices throughout construction, operation, maintenance, renovation, and demolition (EPA, 2016). Numerous rating systems and codes

have emerged to provide high performance building standards and evaluate building sustainability, including Leadership in Energy and Environmental Design (LEED), WELL Building Standard (WELL), the Living Building Challenge, and ASHRAE 189.1 (Green Building Alliance, 2016; Mukhopadhyay, Baltazar, Kim, & Haberl, 2011; Zuo & Zhao, 2014).

While improved certification scores do not guarantee decreased environmental impacts, studies have quantified the benefits of building certifications, particularly increased energy efficiency in LEED certified buildings. The energy reduction achievable by high performance buildings varies, though LEED buildings are demonstrated to produce energy reductions of 10 to 44% when compared to conventional construction (Newsham, Mancini, & Birt, 2009; Suh, Tomar, Leighton, & Kneifel, 2014; Turner & Frankel, 2008). ASHRAE 189.1 (Standard for the Design of High Performance Green Buildings) targets 30% less energy consumption than ASHRAE 90.1 (Standard for Buildings Except Low-Rise Residential Buildings) (Suh et al., 2014). In addition to energy-related savings, benefits of green buildings include increased urban biodiversity (Henry & Frascaria-Lacoste, 2012) and improved construction and demolition waste management (Yeheyis, Hewage, Alam, Eskicioglu, & Sadiq, 2013).

One method for evaluating the environmental performance of buildings is life cycle assessment (LCA). LCA is the process of quantifying the environmental impacts of a product or process throughout its life cycle. While commonly used for assessment of climate change-related metrics, it has the capacity to quantify a range of impacts. When evaluating the energy-related environmental impacts over a building life cycle, most are accrued in the operational stage, as opposed to material production or building construction (Scheuer et al., 2003). However, as operational impacts decrease, holistic building evaluation becomes more crucial as material components begin to contribute a larger share of impacts (Thiel et al., 2013).

Though high performance buildings are the beneficiaries of real or perceived environmental benefit when compared to conventional buildings (Holmgren, Kabanshi, & Sörqvist, 2017), a life cycle approach is required to justify such claims and may reveal areas of environmental concern.

Heterogeneity in building characteristics can make building-focused LCA difficult, frequently limiting its use to the assessment of single building projects. However, there are many situations that involve sets of building stock, such as in municipal or institutional settings, where entities are faced with decisions about how to manage many buildings as they age and ultimately need to be renovated or replaced. Numerous factors inform such decisions, including cost, resource availability, and cultural or historic significance (Thomsen & van der Flier, 2009), but environmental metrics are increasingly important as cities and institutions adopt environmentally-oriented goals or targets.

A potential method for evaluating the environmental merit of new construction projects is comparison to existing, baseline building cases. This can be achieved through the calculation of environmental payback period (EPP). EPP borrows from the economic concept of payback period, defined as the time required to recover an initial financial investment through recurring savings. In the case of building replacement, EPP is the time at which environmental impact savings from new building operations equal initial environmental impacts incurred through construction (Faludi & Lepech, 2012). EPP combines the concept of economic payback and life cycle assessment, creating a means of comparison across a range of impact categories. This provides feedback to decision makers using an easily understood metric. Payback of environmental impacts has been referred to as both environmental and ecological payback period in the literature. In this thesis, the term environmental payback period is used as the

environmental impacts assessed do not have a specific focus on ecosystems, organisms, and biodiversity.

Previous studies have adopted the payback period concept for carbon emissions, coined “carbon payback period”, most of which pertain to the carbon emissions associated with renewable energy production. For example, Gibbs et al. (2008) investigate the carbon payback time for biofuel production in tropical regions, Jonker et al. (2014) assess wood pellet production in the southeastern US, and Lu and Yang (2010) assess greenhouse gas payback time for solar photovoltaic systems in Hong Kong.

Faludi and Lepech (2012) extend the environmental payback period methodology to buildings. Their analysis of a prefabricated modular building includes payback for both carbon and the overall impact score from EcoIndicator 99, a damage-oriented impact assessment methodology, and finds payback times to be on the order of years, not decades. As the first and only study thus far to apply EPP to buildings, it provides insights into the potential environmental benefits of building replacement projects. However, their study was not designed to thoroughly examine EPP as a methodology, identify key contributing factors to EPP, or determine EPP per impact category, all of which are areas that warrant further investigation.

Given the limited use of EPP in previous applications, this project seeks to extend and refine the methodology associated with environmental payback period in the context of commercial and institutional buildings. This project also helps extend LCA methodology by incorporating EPP into impact assessment, with careful consideration given to temporal boundaries and allocation of impacts. This work investigates EPP across a range of impact categories and the materials, processes, and phases of building life cycle that are primary

contributors to each impact. To generate a tool that can rapidly estimate EPP for a set of buildings, it is necessary to determine what factors affect EPP and should be included in such a model. The goal of this work is to identify the conditions under which it is environmentally advantageous to replace an existing building and the environmental impacts most affected by the transition. The project also seeks to quantify the conditions under which an existing, underperforming building should be replaced with new, high performance construction and how long it takes for the environmental benefits of the new building to surpass the impacts from its construction.

Use of EPP as a metric could simplify the application of LCA in the building community, thereby reducing the complexity and difficulty of interpretation (Saunders et al., 2013). A refined EPP calculation methodology could ultimately be extended to a tool to enable the rapid estimation of EPP for a set of commercial, institutional, or municipal building stock. A shorter EPP would flag a building as a potential candidate for replacement. Such a screening tool could identify particular building replacement projects that provide the greatest environment benefits and highlight them as high priority, allowing engineers and planners to conduct further assessments of cost, energy savings, and economic payback to determine the viability of replacement. This targeted approach would help prioritize efforts related to redevelopment, as large scale turnover of buildings is likely to be cost and resource prohibitive.

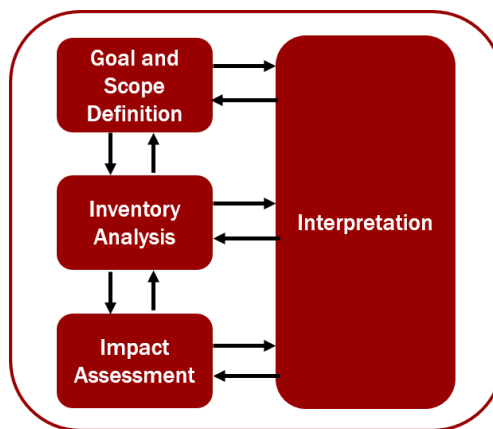
Subsequent sections of this thesis include a review of existing tools and methodologies related to LCA and EPP followed by the development of an EPP framework for buildings, its application to a case study, and a discussion of EPP considerations, implications, and future work.

## 2 MATERIALS AND METHODS

### 2.1 Existing Tools and Techniques

#### 2.1.1 Life Cycle Assessment

Life cycle assessment is an established methodology for quantifying the environmental impacts associated with a product or process. As defined by the International Organization for Standardization (ISO) 14040, LCA is a “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (International Organization for Standardization, 2006a). Guidance on how to conduct LCA is established by the ISO 14040 and 14044 standards, which describe the principles and framework for LCA, as well as requirements and guidelines (International Organization for Standardization, 2006b). The International Reference Life Cycle Data System (ILCD) handbook produced by the European Commission provides further guidance on performing LCA and conforms to the ISO standards (European Commission Joint Research Centre, 2010). LCA consists for four major stages, as illustrated in Figure 1.



**Figure 1. LCA framework diagram. The arrows between stages in the framework highlight the importance of iteration and interpretation throughout the process to revise and refine the analysis.**

Goal and scope definition sets design parameters, including the intended purpose of the analysis, functional unit, system boundary, and key assumptions. Inventory analysis includes

the collection and documentation of data. This involves quantifying inputs and outputs associated with each process within the system boundary and relating them to the functional unit. The impact assessment stage maps the emissions inventory to a more limited set of impact categories, such as global warming potential or acidification, aiding in interpretation. As LCA is an iterative process, interpretation happens throughout the analysis to refine or revise aspects of the previous steps and ultimately produce insights about the system and make recommendations.

Climate change related impacts, specifically carbon emissions and carbon dioxide equivalents, are a commonly used impact category for benchmarking environmental impacts associated with buildings due to their correlation to energy consumption (C. Peng, 2016; Seo & Hwang, 2001). However, databases used in LCA include inventory items that address a wide range of impact categories, and an extensive body of LCA studies on various topics has also focused on other impacts such as acidification or ozone depletion. Climate change related impacts do not capture the full range of impacts generated by buildings over their life cycle, motivating the consideration of other impact categories in building-related studies.

### **2.1.2 Payback Period**

One of many metrics used in the process of making capital investment decisions is payback period. This is an economic metric that estimates the time required for an investment to recoup initial costs through annual savings (Weingartner, 1969). For example, the decision to purchase a piece of machinery rather than lease it could be analyzed via payback period. Mathematically, payback period represents the point at which Equation 1 is satisfied.

$$C_0 = \sum_{t=1}^T \frac{C_t}{(1+r)^t} \quad (\text{Eq. 1})$$

In Equation 1,  $C_0$  is the investment at time 0,  $C_t$  is the revenue at time  $t$ , and  $r$  is the discount rate. Solving for  $t$  produces the payback period, as shown in Equation 2.

$$t = \frac{\log\left[\left(1 - \frac{C_0 r}{C_t}\right)^{-1}\right]}{\log(1+r)} \quad (\text{Eq. 2})$$

While payback is not a comprehensive metric on which investment decisions should be made, it allows for a simple comparison of alternatives. It can also serve as a constraint for investment selection; an investor may choose to only select projects that have paybacks shorter than a designated period of time. The primary shortcoming of this metric is that it does not address the magnitude of the payback. While a payback may be short, the magnitude of cost and savings could also be small. Therefore, alternatives with the same payback period could produce markedly different savings in absolute terms.

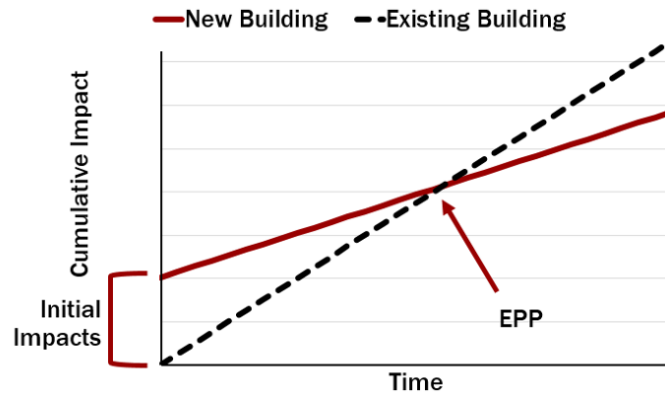
### **2.1.3 Environmental Payback Period**

The concept of payback period has been extended to other quantities, such as energy. In this case, the applicable metric is energy payback, or the point of time at which an energy technology, such as a solar photovoltaic panel, produces as much energy as was consumed throughout the product lifecycle, including manufacturing, transportation, and decommissioning (Lu & Yang, 2010; J. Peng et al., 2013).

The combination of both LCA and payback period principles produces the metric of environmental payback period. Instead of using capital or energy as investments to be reconciled, the framework determines the point at which initial environmental impacts associated with a product or system are equivalent to the environmental impact savings accumulated by use of the product when compared to a conventional alternative. When Equations 1 and 2 are applied to EPP in buildings,  $C_0$  then becomes representative of initial impacts incurred in construction, while  $C_t$  becomes the annual impact savings, or the difference

between the annual impacts from the existing and new buildings. The new building is assumed to have lower operational impacts, creating these savings.

LCA is used to estimate the environmental impacts, which are then utilized within the payback methodology. Figure 2 illustrates a simplified graphical representation of environmental payback period.



**Figure 2. Graphical representation of environmental payback period (EPP) applied to buildings. The slope of each line represents annual operational impacts. The new building incurs initial impacts from construction activities, but its lower operational impacts due to improved efficiency enable the initial deficit to be recovered.**

In this representation, the dashed line and red line represent the cumulative impacts incurred over time by the existing building and new building, respectively. The slope of each line represents the annual operational impact. While the existing building incurs operational impacts only, the new building has a y-intercept representing the initial impacts accrued through the construction processes and materials used in construction. However, the annual operational impacts associated with the new building are less, creating a smaller slope, and the lines ultimately intersect. The x-value of the intersection represents the EPP, after which the difference between the two lines indicates environmental impact savings associated with the new building. Such a representation can be constructed for any single impact for which data is available.

## 2.2 EPP Framework and Case Study

The EPP model used in this study is designed to evaluate the replacement of commercial buildings of comparable size and function. Commercial buildings are selected due to their prevalence and similar use phase characteristics. While renovations and retrofits can improve building performance, this analysis focuses on replacement scenarios. Given the large number of building elements that are candidates for retrofits, this research represents an approach that could later be extended to renovation projects. This EPP model requires the characterization of a business-as-usual case involving the continued operation of the existing building, and the characterization of the construction and future operation of a new building. Both life cycle assessment and payback principles are utilized in this application. This is a multistep process, as illustrated by Figure 3.



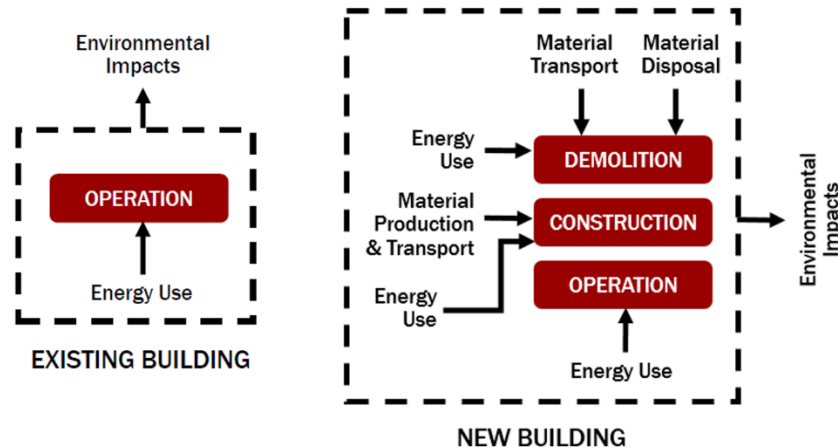
**Figure 3. Environmental payback period (EPP) model workflow. Energy and material data for existing and new buildings are compiled in a life cycle assessment (LCA) model database. Impact assessment is applied using the Tool for Reduction of Chemical and Other Environmental Impacts (TRACI) method, and impact assessment results are transferred to a spreadsheet model from which EPP is calculated.**

The process begins with the collection of building data, including material and energy use components. This data is used in the inventory analysis stage in which it is mapped to database elements from the Ecoinvent 3.2 database. The life cycle impact assessment is performed using open source LCA software, OpenLCA 1.4. Products and processes for each of the aforementioned inputs are included in a database constructed in OpenLCA. Construction and operation are evaluated independently using OpenLCA and Ecoinvent. Aspects of construction are mapped to components in the Ecoinvent database, and a “construction” system is evaluated, the results of which are transferred to the EPP spreadsheet model. The spreadsheet model

contains data on both initial construction and operational impacts, and is used to perform the payback calculation and related sensitivity analysis. This is discussed further in Section 2.2.3. Impact assessment is conducted using the Tool for Reduction of Chemical and Other Environmental Impacts (TRACI), developed by the U.S. EPA. TRACI includes 10 impact categories capturing both environmental and human health factors (Bare, Young, Qam, Hopton, & Chief, 2012). The use of all ten impact categories yields a more comprehensive assessment of building-related impacts when compared to global warming potential alone. Impact assessment results are entered into the spreadsheet model, where variables such as discount rate and energy efficiency changes are altered and EPP is determined.

### **2.2.1 LCA Application**

This project conducts an attributional LCA to quantify environmental impacts associated with new building construction to estimate environmental payback period associated with building replacement. The selected functional unit is one square foot of building floor area. This functional unit addresses the function of commercial buildings to provide workable space, effectively captures differences between new and old buildings, and enables the comparison of replacement projects in which the buildings are different sizes. Figure 4 provides a simplified system boundary diagram for the elements considered.



**Figure 4. System boundary diagrams for existing and new buildings. The model calculates existing building impacts based on energy use, while the model can incorporate demolition, construction, and operational components for the new building impacts. In this study, however, demolition impacts are not included in the EPP calculation.**

The system includes construction and operation and excludes demolition as described in Section 2.2.3. Processes and flows are developed on the whole-building scale. Instead of calculating the required materials per square foot in building construction, the total quantities are input and the impact assessment outputs are then divided by the building square footage to produce impact per functional unit.

Impact values are normalized to aid the interpretation of results across impact categories. This process estimates impacts based on society’s production and consumption activities (Ryberg, Vieira, Zgola, Bare, & Rosenbaum, 2014) using person-equivalents. One person equivalent is the per capita value of the annual impact for each impact category. Normalized values are obtained by dividing the total impact value for an impact category by its corresponding normalization factor to determine the number of person equivalents for that impact. A value of 50 person equivalents, for example, indicates that the given system produces an impact equivalent to 50 people for one year, or one person over 50 years. The normalization

factors used in the project are based on TRACI 2.1 normalization factors, which are derived from Ryberg et al. (2014) and are based on 2008 data for the United States.

### **2.2.2 Case Study**

This analysis uses a newly constructed, LEED certified classroom and administrative building at Wake Tech Community College (WTCC) as the case study for application of the EPP framework. Located in Raleigh, North Carolina, the four story, approximately 49,000 ft<sup>2</sup> building was completed in 2014 and serves the functions of its predecessor, an approximately 48,000 ft<sup>2</sup> building on the campus. The building is oriented on a roughly north-south axis and has a predominantly glass façade. The administrative function of the building closely matches the usage of commercial buildings, and does not include specialty lab space or other functions that may be unusually energy intensive.

### **2.2.3 Model Structure & Data**

The building characterization and model structure includes aspects of building operation of both the existing and new building, as well as construction of the new building. Demolition impacts are not included in the EPP calculations.

#### **2.2.3.1 Construction**

Construction encompasses the materials and on-site equipment operation required for the new building and produces the initial environmental impacts. The construction phase is designed to account for the embodied impacts of construction materials. Construction impacts are not anticipated to significantly affect the impact categories associated with global warming potential, as previous research suggests that most carbon-related impacts are generated during the operational stage (Cabeza, Rincón, Vilariño, Pérez, & Castell, 2014).

The construction materials inventory is developed based on the bill of materials for the building, which was obtained from the project contractor. A previous building LCA study by Thiel et al. (2013) was consulted to determine what material elements to include. Elements of the concrete work, structural and miscellaneous metals, roofing, glass and frames for windows, drywall, flooring, ceiling tiles, plumbing, and HVAC material groups are included. The study does not include sitework (i.e., excavation, site utilities, paving, landscaping, signage) or finishing details (i.e., cabinets, fixtures, doors and hardware, paint, furnishings, electrical). The complete list of materials included in the LCA model can be found in Appendix A1 – New Building Materials.

#### **2.2.3.2 Operation**

The operational component of the model captures the environmental impacts associated with annual energy consumption. This applies to both the existing and new building cases. This component does not account for periodic renovation or maintenance requirements, water use, or materials consumed for tasks carried out in the building, such as cleaning products, office supplies, or appliances.

Energy data for both the existing and new buildings was obtained through the WTCC Facilities Division. Five years of existing building electricity data and three years of new building electricity data were made available, provided as monthly kWh usage. The existing building used fuel oil for heating, and seven years of fuel oil records were made available. The fuel oil was stored in a tank on-site and filled as needed, and records of fill dates and quantities were provided. This data was totaled and divided by the time frame over which it was collected to obtain an annual average fuel oil usage value.

### **2.2.3.3 Demolition**

Demolition processes consider the destruction of a building and transport of resulting wastes to landfill and/or recycling facilities (Cabeza et al., 2014). Often, demolition is considered but not fully quantified in building LCA due to the greater ability to reduce impacts and energy use by making changes in the operational life of buildings (Biswas, 2014; Wang, Shen, & Barryman, 2011). When included, studies demonstrate minor contributions to overall lifecycle impacts (Kofoworola & Gheewala, 2008; C. Peng, 2016). Additionally, limited empirical data on demolition processes exists (Scheuer et al., 2003). Outside the LCA literature, demolition has been considered in the context of waste management in a number of studies (Bergsdal, Bohne, & Brattebø, 2007; Ding & Xiao, 2014; Seo & Hwang, 1999; Wu, Yu, Shen, & Liu, 2014). This body of work does not specifically address environmental impacts, but estimates construction and demolition (C&D) waste for a number of buildings of different vintages, location, and types. The studies develop sets of waste characterization factors by which quantities of material wastes can be estimated based on different building parameters. Such studies serve to determine the load that demolition places on the waste management system, and burdens associated with waste handling. Waste characterization factors can be used in the context of the EPP calculation by using properties of the existing building to estimate the amount of waste associated with the building demolition.

Though the model has the capability to incorporate initial demolition-related impacts in a manner similar to that of construction, they are not considered in the EPP calculation in this study. LCA of a commercial office building conducted by Kofoworola and Gheewarla (2008) found demolition to contribute 0.1% of greenhouse gases, 0.2% of acidification potential and marginal contributions to photochemical ozone formation, while other studies estimate 2 to

4% of CO<sub>2</sub> emissions from demolition (C. Peng, 2016; Suzuki & Oka, 1998). Further qualitative demolition implications, including the allocation of impacts between existing and new building, are considered in Section 5.1.

#### **2.2.4 Base Comparison**

All power needs in the new building are supplied by grid electricity, while the existing building was served by grid electricity supplemented with fuel oil for heating. In this analysis, the existing building energy use was converted to electricity to make a simplified comparison with the new building based strictly on electricity consumption. After making this conversion, the new building was found to use more primary energy than the existing building, and, as a result, the EPP model did not find a payback for any impact categories. This may be attributed to increased building usage as the new building is more inviting and provides greater occupant comfort than the original building, or an introduction of increased plug loads and other technology. To create a scenario in which paybacks can be investigated, a 25% energy reduction between the existing and new building is selected to represent the base case comparison. This value is selected based on existing work that studied the energy performance of LEED and other high performance buildings. Turner and Frankel (2008) found buildings constructed using LEED for new construction guidelines require an average of 28% less energy when compared to the US national average.

A set of building parameters are selected to generate a baseline for comparison, namely a 25% energy reduction between the existing a new building and a 0% discount rate. Results from this base scenario can be compared to those from a series of sensitivity experiments.

### **2.2.5 Energy Reduction**

To quantify the effect of new building energy savings, a range of 0 to 50% energy reduction between the existing and new buildings is implemented by adjusting the primary energy inputs in OpenLCA and transferring the resulting adjusted operational impacts to the EPP model.

### **2.2.6 Discount Rate**

In economics, discount rates are rates applied to future cash flows to determine their present value, enabling comparisons of cash flows that occur at different times. The interest-earning potential makes money more valuable today, which means that the present value of future cash flows is less than or equal to the future value, subtracting out interest. The environmental payback model enables application of a discount rate to quantify the relative value of future impacts at the present time.

While application of discount rates is standard practice in economics and finance, there is much debate over the application of discount rates to environmental impacts. Discount rates can emphasize a difference between near term and long term emissions (Levasseur, Lesage, Margni, Deschênes, & Samson, 2010) and account for some uncertainty (Almansa & Martínez-Paz, 2011). However, ethical implications of valuing future impacts less, and therefore future generations less, is a point of contention. Even discount rates of less than 1% can significantly alter impact results, and their use has been recommended when temporally differentiated data is available, such as emissions patterns as a function of time (Hellweg, Hofstetter, & Hungerbuhler, 2003). Fleurbaey and Zuber (2012) argue for the application of negative discount rates when evaluating climate policies, suggesting that “a dollar of future benefit is worth more than a dollar of mitigation today” (Fleurbaey & Zuber, 2012). Such a position strives to

promote intergenerational equity by considering future generations, and place burdens on current emitters rather than members of future generations.

When considering what may affect EPP, analysis is not only concerned with building performance, but how the environmental effects of the performance are valued. There is much deliberation about whether or not to discount environmental impacts and to what degree. A discount rate analysis is performed by varying the discount rate input into the EPP model within the range of -8 to 8%. Positive discount rates imply valuing future impacts less than impacts incurred today, whereas negative values imply valuing future impacts more than impacts incurred today.

### **2.2.7 Variation in Material Selection**

Changes to building material quantities are conducted to investigate how the materials used in new construction affect EPP. Building material quantities are individually decreased by one percent to determine the percentage change in each building impact category. This is done to individual materials (e.g., copper), as well as building systems (e.g., HVAC). The top five materials producing the largest change for each impact category are chosen for further investigation using EPP. A 25% reduction in each selected material is implemented to determine the corresponding change to EPP. A reduction of 25% is selected to induce a change large enough to affect EPP and assess the relative impact of different materials in the model. This is done by altering the material inputs in OpenLCA and updating the construction module in the EPP model to reflect the new impacts associated with the material changes.

### **2.2.8 Variation in Electricity Supply**

As the electric grid changes over time, transitioning away from coal toward natural gas and renewable resources, the environmental impacts associated with energy supplied to

buildings will also change. While this is a factor that building owners or occupants may not necessarily have control over, it could still affect the future environmental benefits associated with their facilities. An assessment of different electric grid mixes and the evolution of the grid mix over time can determine whether the same benefits anticipated with the current grid mix will stay the same, reduce, or increase given grid changes.

The base case scenario constructed in OpenLCA utilizes the Ecoinvent SERC electricity mix based on 2012-2015 data. To vary different contributions of resources, a manual representation of SERC is developed using the Energy Information Administration's 2017 Annual Energy Outlook (AEO) (Energy Information Administration, 2017) in conjunction with Ecoinvent and OpenLCA. Resource mix data from EIA is included in Appendix A3 AEO 2017 SERC Fuel Mix Data. Use of the manual SERC representation enables the SERC resource mix to be adjusted to reflect changes to the electric grid as estimated by AEO. Though the associated impacts generated using the manual model vary from the Ecoinvent version as shown in Table 1, this manual representation allows for variation in the grid mix over time.

**Table 1. Differences in impacts per kWh for manual and Ecoinvent SERC representations**

<b>Impact Category</b>	<b>Reference Unit</b>	<b>Manual SERC Representation</b>	<b>Ecoinvent SERC Representation</b>	<b>Percent Difference</b>
Acidification	kg SO <sub>2</sub> eq	6.80E-4	6.50E-4	5%
Ecotoxicity	CTUe	0.752	1.21	-38%
Eutrophication	kg N eq	8.00E-4	1.65E-3	-52%
Global Warming	kg CO <sub>2</sub> eq	0.187	0.196	-4%
Human Health - Carcinogenics	CTUh	1.09E-08	1.69E-08	-35%
Human Health – Non-carcinogenics	CTUh	3.12E-08	4.89E-08	-36%
Ozone Depletion	kg CFC-11 eq	2.21E-08	2.11E-08	5%
Photochemical Ozone Formation	kg O <sub>3</sub> eq	4.80E-3	4.47E-3	7%
Resource Depletion - Fossil Fuels	MJ surplus	0.255	0.119	115%
Respiratory Effects	kg PM <sub>2.5</sub> eq	4.99E-05	6.00E-4	-92%

There are a number of discrepancies between the Ecoinvent data, manual SERC data, and powerplant emissions data obtained from the EPA Emissions and Generation Resource Integrated Database (eGRID). This may be attributed to resource variability between SERC sub-regions or data vintage. As the US energy grid rapidly transitions away from coal in some areas of the country, associated environmental impacts will also change from year to year. Thus, results produced here are illustrative of the implications of a cleaner grid, but may not closely match the reality of the current SERC grid.

The two scenarios investigated are based on the AEO Reference Case and AEO Reference Case with the Clean Power Plan. AEO estimates are selected as they represent official U.S. mid-term energy projections and are widely cited in U.S.-focused analyses. The Clean Power

Plan (CPP) is an Obama-era framework setting state-level limits on carbon emissions from power plants. It enables state-level implementation plans and seeks to promote renewable energy generation and energy efficiency (The White House, 2015). Though implementation is on hold as the EPA proposed to repeal the CPP in 2017 (EPA, 2017a), the CPP scenario represents a potential lower-carbon energy pathway, and many states are well-positioned to meet emissions targets despite the absence of federal-level policy (Plumer & Popovich, 2017).

Year 1 of the model is set at 2016, the first year of the AEO case, and is updated with grid mix changes in five year increments beginning with 2020. After 2050, the grid mix is assumed constant in the absence of further AEO estimates for both scenarios. While the AEO Reference Cases provide insights into grid-level changes, this study also considers on-site energy generation. This is simulated through on-site solar power adoption for which SERC electricity was replaced with 100% solar photovoltaics. These scenarios are applied to (1) both buildings and (2) the new building only, in which case the existing building receives all electricity from the SERC grid. For grid transition cases, the updated electricity supply is implemented by adjusting resource quantities in the manual SERC mix in Ecoinvent and transferring the impact results to the operations module of the EPP model, and the solar cases utilize the AEO 2016 Reference Case values.

### **2.2.9 Building Efficiency**

Building energy use may change over time, either decreasing due to energy efficiency improvements, or increasing as systems age and become less efficient. This model considers a multi-decade time frame over which the performance of buildings is likely to change, and enables the implementation of an annual change in energy consumption. Changes to building efficiency in the model are a means of accounting for operational changes over time, both in

the new building and the existing building. The user may input a unique percentage value for both the existing and new buildings, representing an annual anticipated change in energy consumption. This simulates how building owners or occupants can undertake energy efficiency projects and improve energy consumption over time, or how buildings begin use more energy as systems become less efficient, lack proper operations and maintenance, or plug loads are added. This approach is taken for simplicity and flexibility, and percent reductions are not tied to a specific technology choice or energy reduction strategy.

This functionality is included to determine how closely realized building performance must conform to the projected performance of the design to achieve the anticipated environmental benefit, captured in terms of EPP. Similarly, the effect of energy efficiency improvements to an existing building on EPP is also considered. Changes are modeled by varying the increases in efficiency for the existing building and decreases in efficiency for the new building in the EPP model. These values are incrementally changed to examine the point at which each impact category no longer pays back, thus determining which impact categories are most sensitive to such operational changes. Increases to existing building efficiency and decreases to new building efficiency are varied separately (e.g., existing building efficiency is varied with new building efficiency held constant). These changes are not tied to specific new materials or systems and their associated impacts.

#### **2.2.10 Spreadsheet Function**

A series of computations to determine EPP are performed after transferring impact assessment outputs from OpenLCA to the spreadsheet model. For the existing building, only operational impacts are assessed. These begin in Year 1, defaulting to the same value for each subsequent year. For the new building, both operational impacts and impacts from construction

are considered. The model defaults to assigning construction impacts and existing building operational impacts to the first year in the model, with new operational impacts beginning in Year 2. This accounts for the fact building occupants will need to be housed during the new building construction, producing operational impacts during that time. As with the existing building, the same operational impacts are assigned to each subsequent year in the model. From a decisionmaking perspective, this captures the impacts associated with the site on which the replacement project takes place in the business-as-usual and new building cases.

Changes to energy efficiency alter the operational stage environmental impacts. The calculation is included in Equation 3, where  $I$  is the annual environmental impact for a specific impact category,  $n$  is the year, and  $\Delta E$  is the annual improvement in energy use, given as a percentage:

$$I_{n+1} = I_n * \left(1 - \frac{\Delta E}{100}\right) \quad (\text{Eq. 3})$$

Thus, if energy use improves by 0.5% annually, the environmental impacts will decrease by 0.5% annually. After energy use adjustments are made, the model applies a discount rate and determines cumulative discounted impacts using Equation 4, where  $P$  is the cumulative “present worth” of impacts,  $I_n$  is the impacts occurring in year  $n$ , and  $i$  is the discount rate:

$$P = \sum_{n=1}^N I_n (1 + i)^{-n} \quad (\text{Eq. 4})$$

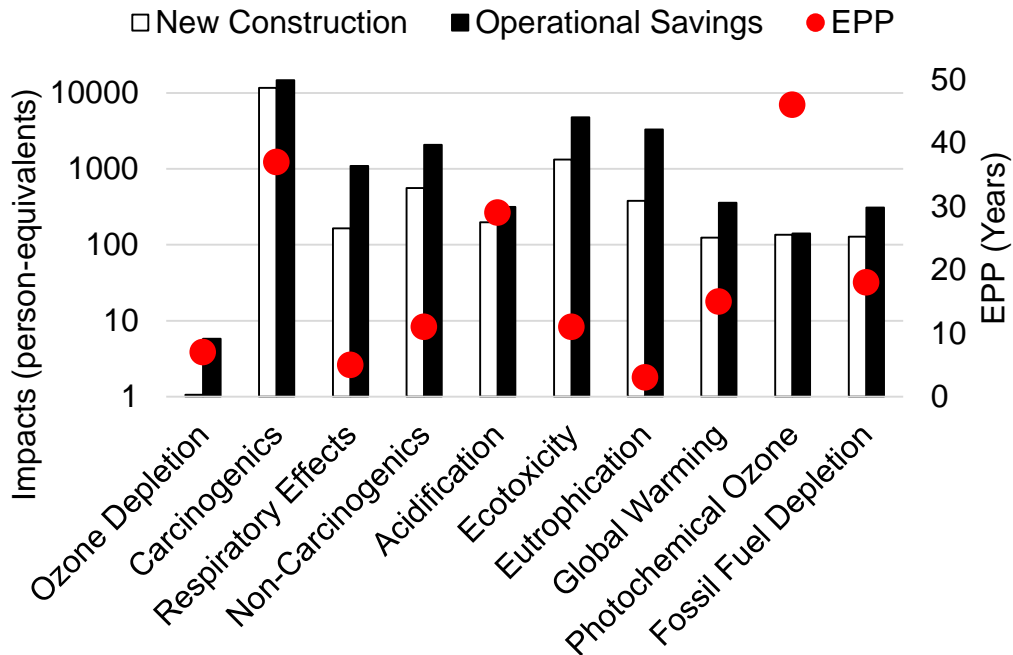
In the base case, where there are no changes in energy efficiency and no discount rate, cumulative impacts for both the new and existing buildings follow a linear function. The non-base case scenarios are more complex due to the introduction of energy efficiency changes and discount rate. EPP is determined through numerical comparison of spreadsheet output instead of through use of a closed-form analytical expression.

In addition to EPP, the normalization of cumulative 50 year impacts to person-equivalents serves as a benchmark for building performance. Negative normalized values indicate cumulative impact savings, or avoided impacts, while positive values indicate an increase in impact from the new building when compared to the existing building. While EPP produces an easy to understand means of comparison, normalized impacts enable assessment of impact magnitude and more insightful interpretations when used in conjunction with EPP. For example, an impact category with a short EPP but a small normalized magnitude would indicate that the change is not especially impactful, while a larger normalized magnitude and short payback would indicate a larger beneficial change. Alternatively, a long EPP that alone may appear problematic may also be considered less impactful when coupled with a small normalized magnitude. By using these two metrics together, decision makers can avoid making decisions based solely on EPP that do little for impact mitigation.

### **3 RESULTS AND DISCUSSION**

#### **3.1 Base Comparison**

Results for the base case scenario of 25% energy reduction, 0% discount rate, and both buildings powered by 100% grid electricity are given in Figure 5. EPPs exist for all impact categories in this case but vary by impact category: photochemical ozone formation has the longest EPP at 50 years, while eutrophication is the shortest at 7 years. Evaluating any of these impacts in isolation could give a misleading impression of the overall environmental benefit of this replacement project.



**Figure 5. Base case environmental payback periods, normalized impacts from initial construction, and normalized 50 year cumulative impact savings. Photochemical ozone formation has the longest EPP of 50 years, while eutrophication has the shortest at 7 years. Cumulative impact savings, plotted on a log scale, span orders of magnitude with ozone depletion as the smallest and carcinogenics as the largest. The pairing of EPP and normalized impacts highlights the lack of correlation between impact magnitude and payback.**

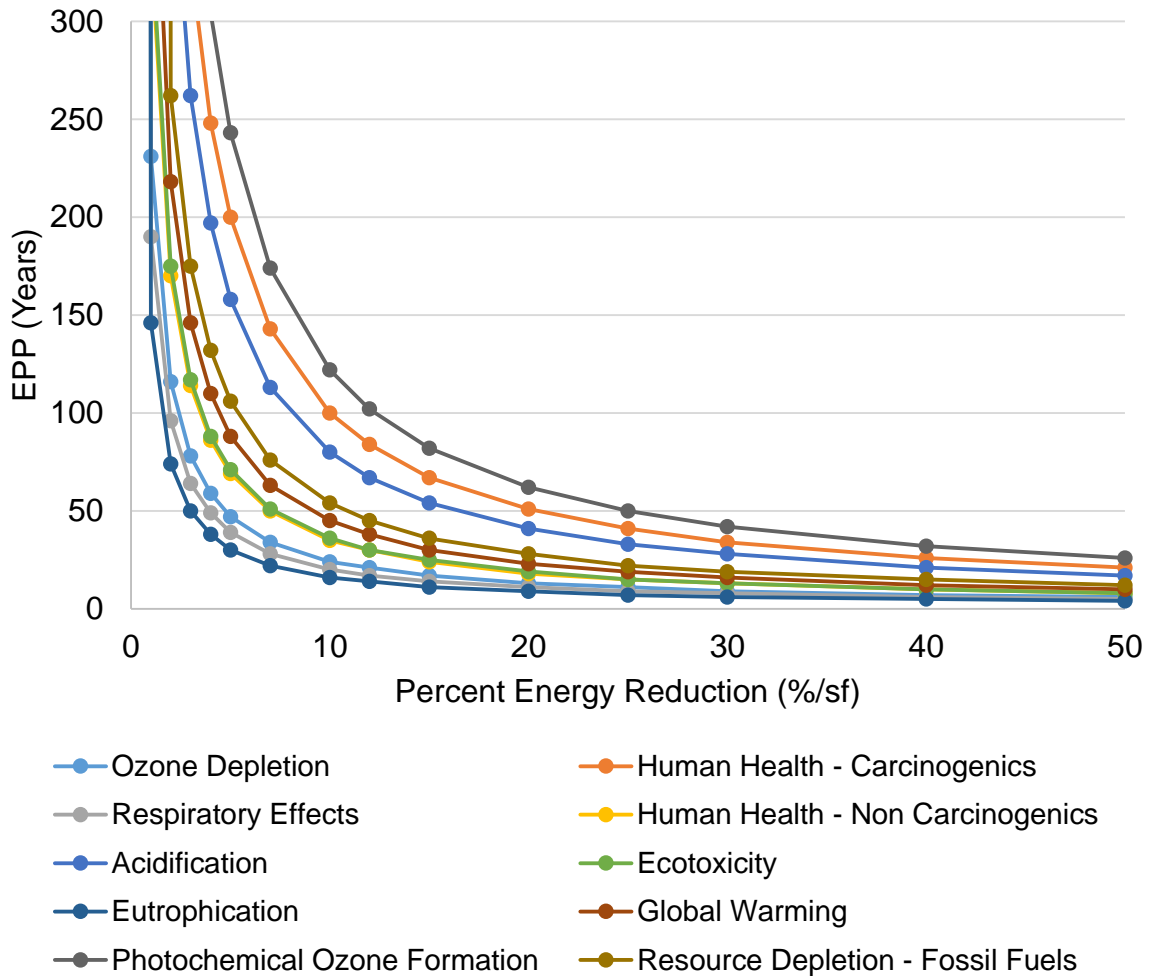
In Figure 5, instances where operational savings exceed initial construction impacts are indicative of an EPP of 50 years or less. Pairing EPP with normalized impacts highlights the lack of correlation between impact magnitude and payback. Eutrophication has the shortest EPP and third greatest impact savings, indicating it is highly advantageous to undertake the replacement project for this impact. Conversely, photochemical ozone has the longest payback period and only modest impact savings, indicating that it is among the least beneficial. Ozone depletion, with a short payback and small impact savings, would provide less motivation for undertaking a replacement project.

These results also highlight the contrast between climate and toxicity impacts. Global warming potential is a category often associated with green building projects and it has a

moderate payback of 19 years, supporting its use in this application as it makes the project appear advantageous. However, the 50 year cumulative savings are modest, 360 PEs, or approximately 7 per year. At the same time, carcinogenic impacts have a payback of over twice as long at 41 years, indicating a lesser advantage to building replacement, while the normalized cumulative savings exceed 10,000 PEs. Ecotoxicity also exhibits a high quantity of impact savings. While human health impacts, including carcinogenics, non-carcinogenics, and respiratory effects, are more uncertain and not typically addressed in green building assessment, Figure 5 indicates that they are non-negligible.

### **3.2 Energy Reduction**

Greater energy reduction in the new building relative to the existing one corresponds to a decrease in EPP as illustrated in Figure 6. Each line represents an impact category. A constant discount rate of 0% is applied. Points are sampled with a higher frequency within the 0 to 15% reduction range to capture the shape of the EPP decrease.



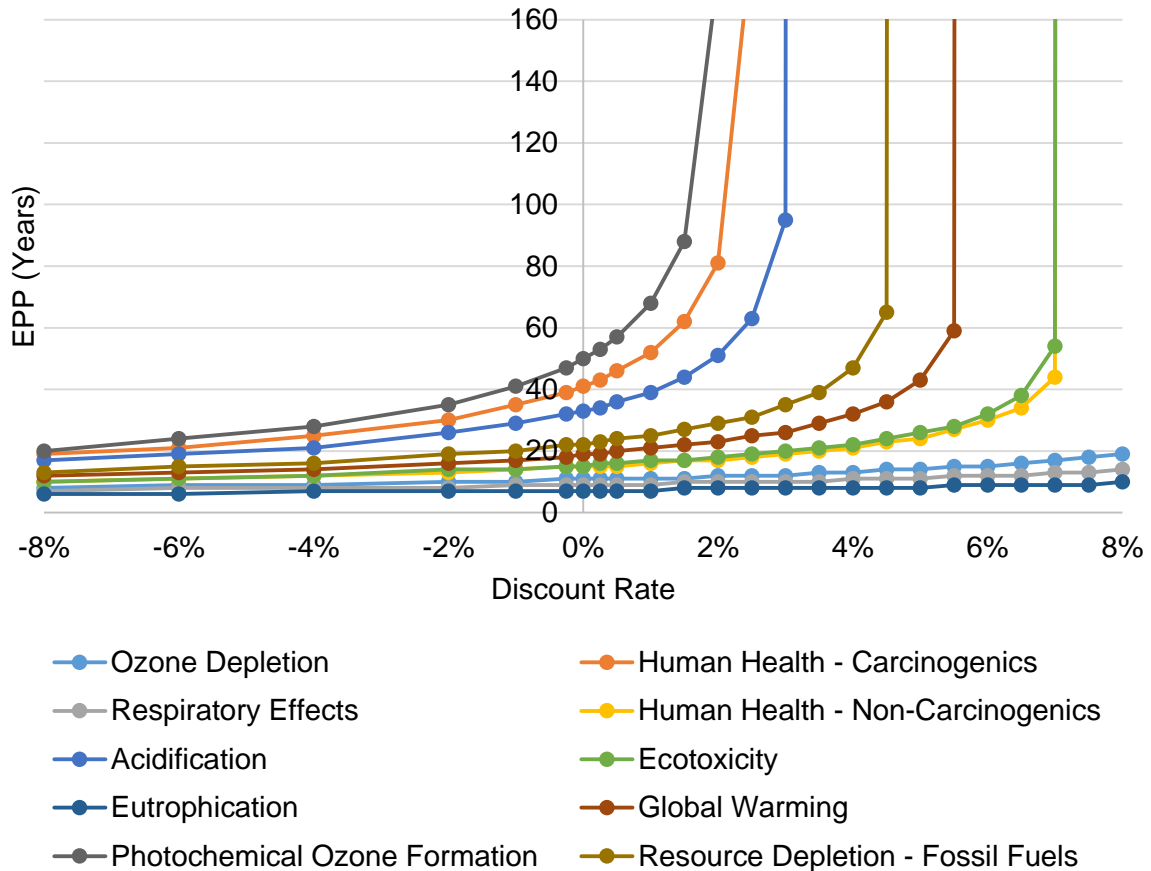
**Figure 6. Percent energy reduction versus environmental payback period for TRACI impact categories. Increases in the annual percent energy reduction in the new versus existing building produce non-linear decreases in EPP.**

Given that electricity is assumed to be used exclusively in both the existing and new buildings, no paybacks are obtained at a 0% energy reduction since the new building introduces new impacts through construction and does not have a mechanism for operational impact savings. The relationship between percent energy reduction and EPP is not linear; as energy reduction increases, there is incrementally less benefit per unit energy reduction. However, the sensitivity to energy reduction varies by impact category; photochemical ozone formation and carcinogenic impacts are more sensitive to the change, while respiratory effects and eutrophication experience less change. A 15% decrease in energy consumption between the

old and new buildings reduces EPP for all impact categories except photochemical ozone formation to within a projected building lifetime of 80 years. However it takes a 50% energy reduction to reduce EPP to a more near-term timeframe of under 30 years across all impact categories. These results indicate that energy reductions achieved by buildings in previous studies can produce increased environmental performance as represented by shorter EPPs across all impact categories.

### **3.3 Discount Rate**

Increases in discount rate increase EPP exponentially, such that they approach vertical asymptotes. At a sufficiently high discount rate, the present value of annual impact savings does not offset construction impacts. The discount rate values at which this happens vary by impact category as shown in Figure 7. Each line represents an impact category and the percent energy reduction is held constant at 25%. The discount rate at which the line approaches an asymptote represents the rate at which there is no longer a payback; the existing building is preferable to new construction for that impact category at that rate.



**Figure 7. Percent discount rate versus environmental payback period for TRACI impact categories. Increases in discount rate produce non-linear increases in EPP. At an 8% discount rate, the highest rate considered, only ozone depletion, respiratory effects, and eutrophication all have finite discount rates under 20 years.**

Figure 7 also illustrates that negative discount rates further improve EPP, though the improvement is modest for all impact categories over a wide range of negative rates. If future impacts are valued less than impacts today, represented with a positive discount rate, the annual impact savings decrease, which increases the amount of time it takes to pay back impacts. As discount rate approaches a market rate, it becomes less likely that a decision maker would opt for building replacement. However, if future impacts are valued more than impacts today, represented with negative discount rates, then those savings increase over time, shortening payback.

A determining factor in sensitivity to discount rate for an impact category is the ratio of initial impacts to operational impact savings resulting from a more efficient new building. This is reflective of the mathematical relationship contained within Equation 2 between  $C_0$  and  $C_t$ , where  $C_0$  is initial impacts, and  $C_t$  is annual impact savings.

This ratio is increased by increasing initial impacts or decreasing annual impact savings. Conversely, it is decreased by decreasing initial impacts or increasing annual impact savings. This means that short EPPs are the result of either low initial impacts, high operational savings, or a combination of the two for a particular impact category. Thus, EPP can be influenced by all building life cycle stages, and designers have the option to either target initial or operational impacts if trying to reduce EPP. Table 2 includes the impact ratios and EPPs for the base scenario.

**Table 2. Impact ratios for 25% energy reduction and 0% discount rate**

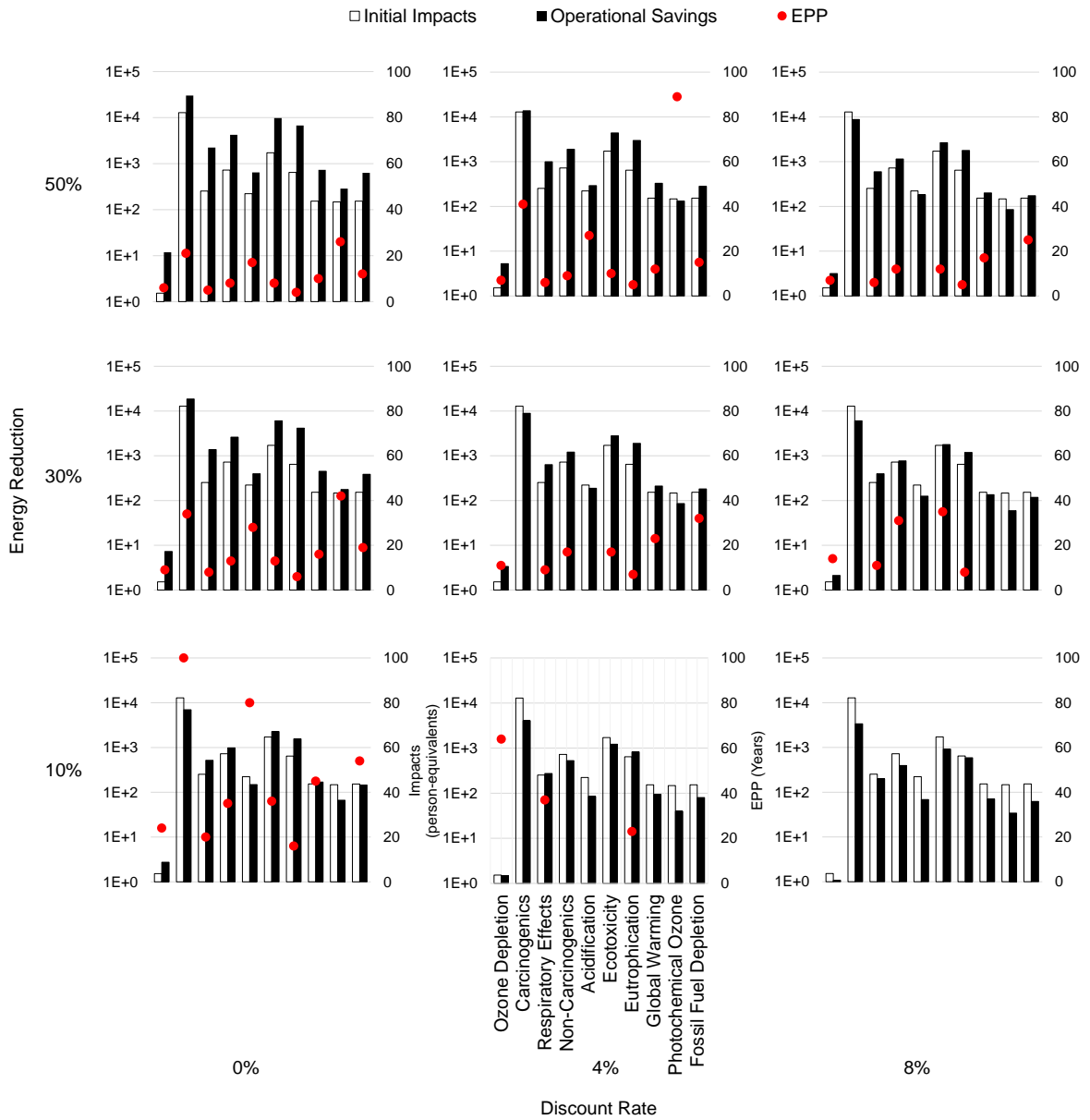
<b>Impact Category</b>	<b>Impact Ratio (<math>C_0 / C_t</math>)</b>	<b>EPP</b>
Ozone Depletion	9.15	11
Carcinogenics	39.6	41
Respiratory Effects	7.54	9
Non-carcinogenics	13.5	15
Acidification	31.3	33
Ecotoxicity	13.9	15
Eutrophication	5.78	7
Global Warming	17.3	19
Photochemical Ozone	48.4	50
Fossil Fuel Depletion	20.8	22

Interpreted in conjunction with Figure 7, it is shown that impacts with higher ratios are more sensitive to discount rate and tend to have longer EPPs, while lower ratios are less sensitive to discount rate and tend to have shorter EPPs. High ratio, more sensitive impact categories include photochemical ozone formation and carcinogenics, while low ratio, less

sensitive impact categories include eutrophication, respiratory effects, non-carcinogenics, and ecotoxicity. These results further illustrate the significant differences in impact across different impact categories.

### **3.4 Interaction of Energy Reduction and Discount Rate**

Additional model runs are conducted to investigate the interactions between the assumed annual energy reduction and discount rate. After pairing different discount rates with percent energy reductions, options for shorter EPPs begin to emerge. Figure 8 illustrates the sensitivity of EPP to both discount rate and energy reduction. Energy reductions of 10%, 30% and 50% were tested in conjunction with discount rates of 0%, 4%, and 8%. The absence of a red circle for an impact category indicates that there is not an EPP for that impact under the given conditions.



**Figure 8. Environmental payback period and normalized 50 year cumulative impact savings when percent energy reduction and discount rate are varied simultaneously. EPP is represented on the left axis and normalized impacts on the right. The absence of a red circle for an impact category indicates there is not a payback under the specified conditions. Low discount rates and high energy reduction produce outcomes in which all impact categories pay back. Category labels shown in the bottom center figure apply to all figures.**

Lower discount rates and higher energy reductions produce more optimal EPP scenarios. In the cases shown, all impacts have paybacks for the 0% discount rate column with the exception of photochemical ozone formation with 10% energy reduction, while 3 to 10

categories do not recognize paybacks in the 8% discount rate column. This illustrates that the less a decision maker values future impacts, the better performing the new building must be to recognize paybacks. Figure 8 also illustrates the decrease in cumulative impact savings as percent energy reduction decreases and discount rate increases.

### 3.5 Variation in Material Selection

Preliminary analysis on the effect of different building materials on environmental impact produced seven materials for further investigation: aluminum, glass, concrete, steel, iron, copper, and terrazzo (composite flooring material). These materials are individually decreased by 25% in OpenLCA and the percent decrease in EPP in each case is calculated and included in Table 3. Shaded cells highlight instances of EPP decrease as a result of material decrease.

**Table 3. Percent change in EPP due to 25% decrease in material input**

<b>Impact Category</b>	<b>Aluminum</b>	<b>Glass</b>	<b>Concrete</b>	<b>Steel</b>	<b>Iron</b>	<b>Copper</b>	<b>Terazzo</b>
Ozone Depletion	18%	9%	9%	9%	9%	0%	0%
Carcinogenics	15%	0%	0%	7%	0%	0%	0%
Respiratory Effects	11%	0%	0%	0%	0%	0%	0%
Non-Carcinogenics	13%	0%	0%	7%	0%	7%	0%
Acidification	15%	3%	3%	3%	3%	0%	3%
Ecotoxicity	7%	0%	0%	0%	0%	0%	0%
Eutrophication	14%	0%	0%	0%	0%	0%	0%
Global Warming	16%	0%	0%	0%	5%	0%	0%
Photochemical Ozone	14%	2%	2%	2%	4%	0%	2%
Fossil Fuel Depletion	9%	0%	0%	0%	0%	0%	0%

Each of the assessed materials are present in different quantities in the building, some representing larger fractions of total weight or volume of the building than others. Additionally, 25% reductions in any given material would likely be hard to achieve, so these values are meant to be representative of the relative impacts by material.

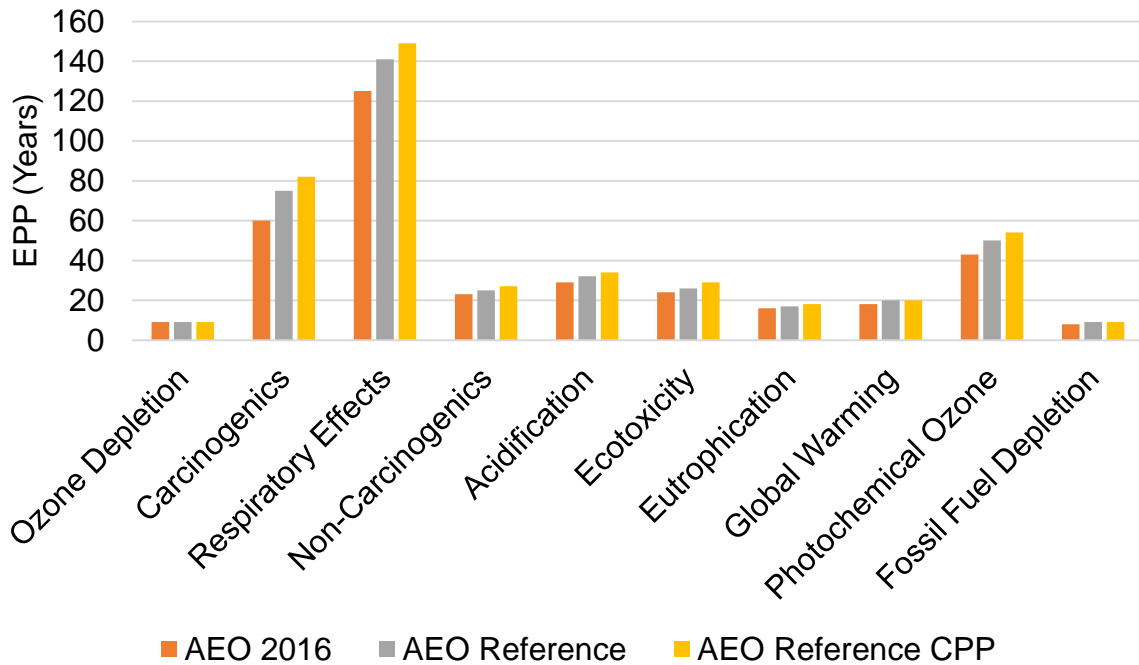
Large changes in material produce only modest changes in EPP, implying material selection is not a primary factor for determining EPP. All material reductions of 25% produced EPP reductions of less than 25%. The effect of each material on the overall building varies by material. Decreasing aluminum results in a decreased EPP across all impact categories, steel decreases 5 impact categories, and iron decreases 4 categories, while other materials affect 3 or less. Similarly, some impact categories are affected more than others. Ozone depletion is affected by 5 of 7 materials examined, with a 9% or more decrease in EPP. Acidification and photochemical ozone formation were both affected by 6 of 7 materials, though with more modest EPP decreases.

The impact of aluminum is attributed to the environmental burdens associated with bauxite mining, alumina production, and processing of alumina to aluminum. These refining, smelting, and casting processes are each energy intensive and waste producing. For example, one ton of alumina production creates as much as two tons of “red mud”, a toxic byproduct (Tan & Khoo, 2005). Thus, decreasing the quantity of aluminum in the building significantly decreases the associated impacts.

### **3.6 Variation in Electricity Supply**

Implementation of cleaner grid-level energy changes produces longer EPPs. Through 2050, the AEO anticipates a shift toward cleaner energy production. These improvements to the grid increase EPP, as cleaner energy production applied to both scenarios reduces the

amount of savings achieved by operating a new building. Thus, an EPP based on the current grid mix is shorter than one based on the anticipated future grid mix, as illustrated in Figure 9.

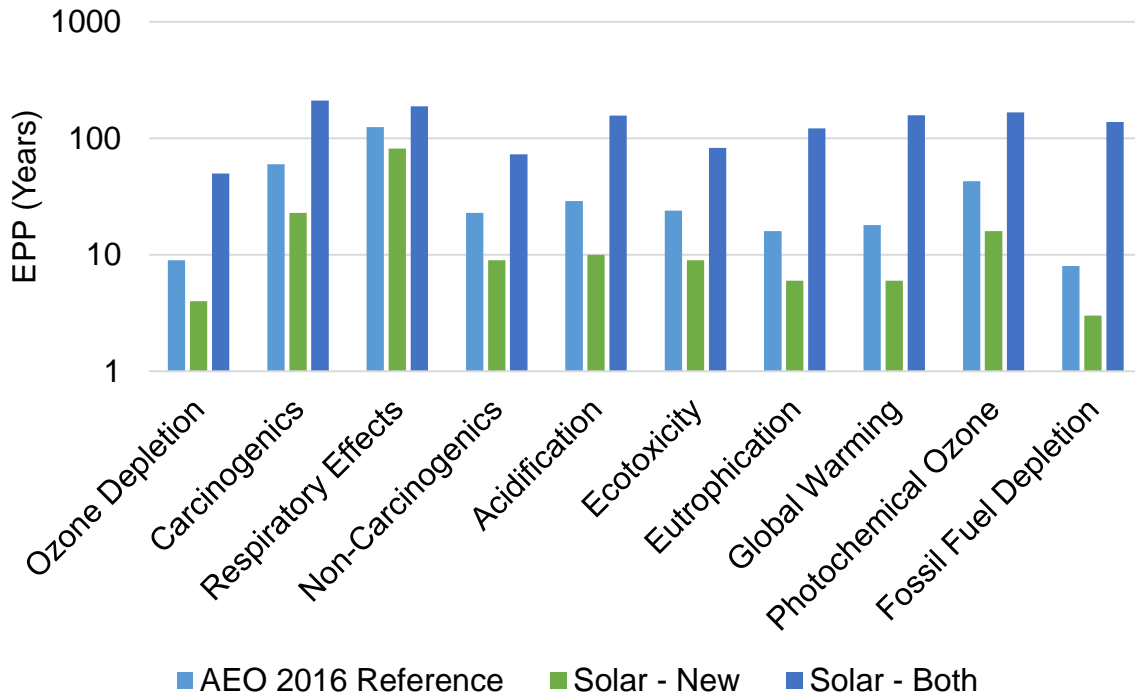


**Figure 9. Effect of grid transition over time on environmental payback period. As the electric grid becomes cleaner, EPP increases due to decreased impact savings between the existing and new building. Note that the grid mix is assumed to remain constant at the AEO 2016 value, while the other two scenario assume a changing grid mix over time based on the AEO Reference and Clean Power Plan (CPP) scenarios. The AEO 2016 mix is the same as the manual SERC mix contained in Table 1.**

Transition to the 2050 AEO Reference Case mix from the 2016 AEO values produces a EPPs of 100 to 125% of the base value depending on impact category. Similarly, a transition to the 2050 AEO Reference Case with CPP, a scenario with larger renewables deployment, leads to EPPs of 100 – 137% of the base value. It should be noted that the model produces EPP at the resolution of one year, so it is possible that impact categories that did not experience a change in EPP due to fuel supply changes may actually change slightly, but not enough to be reflected in the model output. This is confirmed via graphical interpretation of the EPP results.

A similar trend is observed for the application of solar to both buildings as illustrated in Figure 10. The 100% solar scenario applied to both buildings increases EPP to an average of

over 8 times longer compared to using the AEO 2016 scenario. However, the opposite is observed for changes that are applied to the new building only. If only the new building receives electricity via solar, EPP drops to an average of 40% of the AEO 2016 scenario.

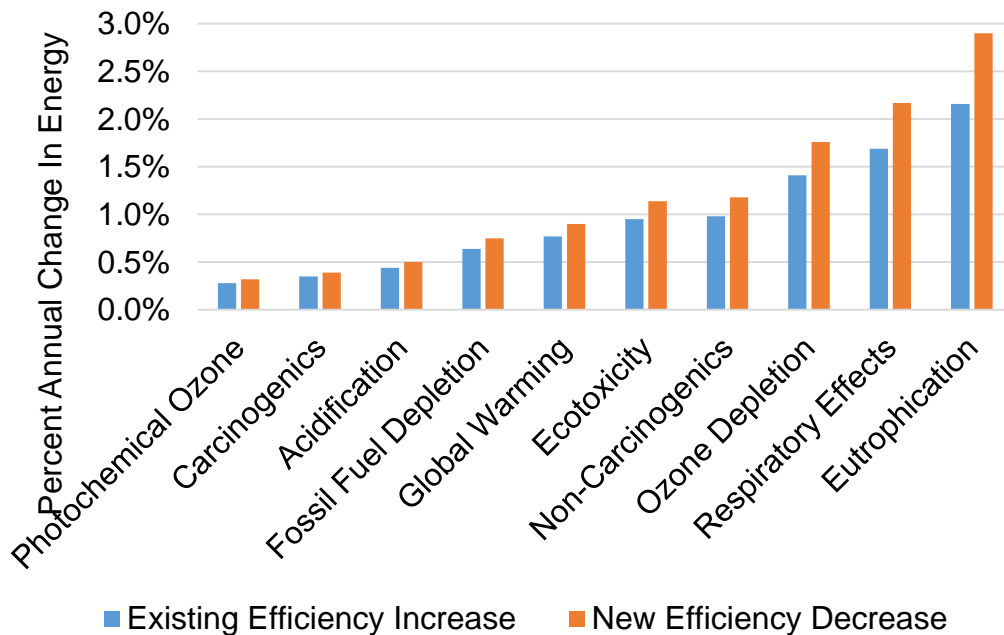


**Figure 10. Effect of 100% solar electricity supply on environmental payback period when applied to just the new building (green bars) and to both buildings (dark blue bars). EPP is plotted on a log scale. Application of solar to the new building only reduces EPP, while application to both buildings increases EPP.**

Thus, all electricity supply changes are not created equal with respect to EPP. It is important to consider the differences between improvements to the new building, such as distributed renewable generation, and grid level improvements. Energy efficiency is found to be less valuable on a cleaner grid, though this effect is magnified by the consideration of electric-only buildings. The inclusion of fuel oil or natural gas heating would dampen the response.

### 3.7 Building Efficiency

Annual changes in energy usage are varied to determine the percent annual energy reduction in the existing building or annual energy increase in the new building that would eliminate EPP for different impact categories, meaning there is no longer a payback. Figure 11 illustrates the wide range of change required to elicit EPP elimination for different impact categories in the 25% energy reduction, 0% discount rate scenario.



**Figure 11. Comparison of changes to energy efficiency required to eliminate payback for specified impact categories, assuming 0% discount rate and an initial energy reduction of 25% between buildings. Impact categories with smaller allowable changes must operate closer to the designed and anticipated performance to maintain payback, whereas larger changes indicate payback is less sensitive to changes in annual energy use.**

A small change in photochemical ozone or carcinogenics, for example, results in the elimination of EPP, meaning that new buildings must operate closer to design to experience an anticipated payback. Similarly, small improvements in the existing building would make renovation preferable to replacement. Conversely, the model indicates that larger changes to energy performance can still produce payback on ozone depletion, respiratory effects, and

eutrophication. Additionally, a greater change in the new building than the existing building is required to eliminate payback. This is because the new building consumes less energy, so a percent change in the new building corresponds to proportionally less energy and associated impacts compared with the same percent change in the existing building.

For comparison, a 1% change corresponds to 9797 kWh and 7348 kWh in the existing a new buildings, respectively. To put this in perspective, the switch from a single fluorescent lightbulb to an LED lightbulb produces a 9W savings. Operating 12 hours per day, five days per week would equate to a per-light savings of 28 kWh/year. Thus, 350 lightbulbs would need to be switched from fluorescent to LED to produce this annual decrease. For a switch from incandescent to LED, the number of bulbs to switch decreases to 58. This decrease could not be sustained over the lifetime of the building by changing lightbulbs alone, for example. A number of other options, such as changes to HVAC systems or the building envelope, could also provide efficiency improvements.

A similar analysis is conducted for the 50% energy reduction, 0% discount rate scenario and finds the permissible percent changes to be larger, illustrating that the performance buffer increases as percent energy reduction increases, and more drastic changes are required in the 50% scenario than the 25% reduction scenario to eliminate EPP.

This analysis considers energy efficiency improvements and declines by implementing an annual change in efficiency for the entirety of the building lifetime. Such a representation is clearly simplified. Owners and property managers are likely to periodically implement changes in a stepwise, rather than incremental fashion. Instead of replacing a handful of lightbulbs a year, for example, the owner may replace all the lightbulbs for an entire floor or building.

Similarly, updating appliances or replacing windows would produce a step change, rather than gradual, decrease in energy use.

## **4 IMPLICATIONS**

### **4.1 Green Building Rating Context**

As the usage of green building rating systems in construction projects becomes more common, the inclusion of LCA in such rating systems provides an opportunity for evaluation and mitigation of environmental impacts from building construction and operation. One of the most popular rating systems is Leadership in Energy and Environmental Design (LEED), which outlines actions that can be taken in projects to make them more resource-conscious and environmentally friendly through a series of credit categories. Buildings receive different certification levels (i.e. Certified, Silver, Gold, or Platinum) based on the number of points obtained through credits pursued.

The newest version of LEED Building Design and Construction (BD+C) guidelines, LEED BD+C v4, incorporates a credit for LCA in the “Materials and Resources” category. However, the credit is included to aid in material-based decisions and does not address lifetime energy or operational impacts. The credit is achieved if the material choices demonstrate a 10% reduction in global warming potential as well as a 10% reduction in 2 of 5 other impact categories, including ozone depletion, acidification, freshwater eutrophication, photochemical ozone formation (tropospheric ozone), and depletion of nonrenewable energy resources (U.S. Green Building Council, 2013). The addition of this credit satisfies a need to compare materials with varying environmental impacts.

Other LEED credit categories, such as “Energy and Atmosphere,” contain provisions for energy reduction in building operations. However, this is evaluated independent of the LEED

LCA component, and the environmental impacts of energy reduction are not assessed. The absence of operational impacts in the LEED building LCA prevents the assessment of the true, total building-related impacts within the rating system. LCA in LEED is, in effect, an LCA of embodied material impacts, not a comprehensive LCA of a building over the course of its lifetime. Additionally, the credit is outlined in such a way that it could fall victim to gamification of the LEED points system. Baseline materials are not provided, so theoretically, the least environmentally preferable materials could be selected for the baseline to achieve the prescribed decreases through improved material selection.

This lack of comprehensive building assessment creates a gap which more accessible building LCA methods or evaluation tools, such as EPP, could fill. Without such a tool, LEED fails to quantify and evaluate the potential environmental benefit of buildings certified by this system. Within the LEED context, use of EPP could tie together aspects of the Materials and Resources and Energy and Atmosphere credit categories by requiring evaluation of both material and operational impacts to estimate EPP for specified impact categories.

#### **4.2 Shortcomings of EPP**

EPP provides an easily interpreted comparison for existing and new building operation, but has its own limitations. A primary limitation is that payback period does not address impact magnitude, as discussed in Section 2.1.2. Alternatives with the same payback period could produce markedly different savings in absolute terms, so the coupling of EPP with normalized impacts is valuable for improved EPP interpretation. EPP simply provides a payback time, and it is left to the discretion of the decision maker which, if any, impact categories should be prioritized based on organizational preferences.

Additionally, EPP is dependent on the relative performance of two options. In theory, the replacement of a poor-performing building with a building of average performance and the replacement of a building of average performance with a high performance building could produce the same EPP. EPP is illustrative of improvement, not standalone performance, and it thus cannot be used as a universal metric to compare different buildings, only different replacement projects. EPP does not address where, geographically, impacts are incurred in the same way that a comprehensive LCA would. Care must be taken to ensure results are not misconstrued to describe local impacts, but instead the impact contributions to the larger global system.

Lastly, EPP does not account for end effects, whereby interactions between different impact elements affect payback over time. In general, payback is only concerned with the first intersection of business-as-usual and the investment case, and doesn't involve the subsequent activities and effects. This is illustrated when discrete changes to building energy consumption are introduced over time. The model captures the initial point at which the new building becomes preferable to the existing building, but not the point at which the existing building may overtake the new building as more preferable due to changes. As a result, the time horizon of evaluation matters, as the case that may look favorable over a 25 year time horizon may not also be preferable when evaluating over 50 years, for example. However, this critique does not apply for evaluation of a constant percent energy difference between an existing and new building.

### **4.3 Comparison to Existing Literature**

Studies applying EPP to building replacement are limited in number. Faludi & Lepech (2012) use EcoIndicator99 to assess the demolition of a community center building and

subsequent replacement with a 5,000 square foot prefabricated, modular building. They find a carbon payback of 11 years, and a total EcoIndicator99 payback of 20 years. Comparatively, results here produce a payback on global warming potential (CO<sub>2</sub>-eq.) of 15 years and an average payback across all 10 impact categories of 18 years in the base case. While the scenarios evaluated in these two studies differ, the comparable results help validate the EPP results presented here.

In a broader LCA context, the discussion of environmental impacts related to buildings is dominated by addressing the operational stage of buildings. Findings related to EPP confirm the importance of the operational stage in estimating lifetime impacts: it is through the operational stage that impact savings can be recognized. Sensitivity to energy reduction also highlights the importance of the operational stage, as decreases in energy use produce exponential reductions in EPP for some impacts. For example, a 10% annual energy reduction corresponds to EPPs of 112 and 70 years for photochemical ozone formation and acidification, respectively, while a 50% annual reduction decreases these values to 24 and 15 years.

The results presented here extend the previous findings by addressing a range of environmental impacts, including human health. By employing EPP methodology for a number of impacts, decision makers can guard against burden shifting, or the reduction of one impact while simultaneously increasing another. Normalized impacts show buildings make notable contributions to both carcinogenic and non-carcinogenic human health impacts, ecotoxicity, and eutrophication, all of which have greater operational savings than global warming potential when comparing person-equivalents and represent localized environmental impacts from buildings. Such insights are neglected when evaluating global warming potential alone. It is worth noting, however, that there is more uncertainty embedded in human health

and toxicity related impacts than global warming potential, acidification, or resource use (Dreyer, Niemann, & Hauschild, 2003).

#### **4.4 Other Temporal and Discount Rate Considerations**

Careful consideration of temporal effects on pollution is important and can have an effect on EPP. This is especially true of global warming potential (GWP) and greenhouse gases given their long residence times in the atmosphere. In the TRACI impact assessment methodology, GWP is the only impact category that requires a forward-looking, multi-decadal timescale to assess impact. Other impact categories are not affected in this way as their contributing pollutants have residence times on the order of hours, days, or months. For example, the residence time of sulfur dioxide, a primary contributor to acidification, is approximately half a day (Cuong, Bonsang, Lambert, & Pasqueir, 1975).

Greenhouse gases are differentiated by their radiative efficiency, or ability to absorb energy, and their lifetime, or amount of time they remain in the atmosphere. GWP is the amount of energy that a mass of a specific greenhouse gas absorbs over a given timeframe when compared to the same mass of CO<sub>2</sub>. In the TRACI methodology, a 100-year timescale is considered, though 20-year timescales are also considered in other methodologies (Bare et al., 2012; EPA, 2017b) When calculating GWP associated with annual emissions, the GWP is a scalar representation of the integrated effect of those annual emissions over a 100-year timescale. This integrated effect is used to develop the characterization factor for different greenhouse gases, such as methane (CH<sub>4</sub>). Shorter timescales magnify the effect of gases with shorter lifetimes than CO<sub>2</sub>, increasing their global warming potential. For example, CH<sub>4</sub> has a lifetime of approximately 12 years and a 100-year GWP of 28 to 36, but a 20-year GWP of 84

to 87 (EPA, 2017b). Thus, the selection of a shorter time scale can alter impacts, and in turn, affect EPP.

Using the standard TRACI methodology, the radiative effect of different greenhouse gases is not explicitly discounted. Thus, the undiscounted, integrated effect of a particular greenhouse gas over a given time horizon (e.g., 100 years) is collapsed into a scalar value. In this case study, the GWP for a given year actually represents the radiative effect of greenhouse gas emissions over the next 100 years. This undiscounted GWP value is then applied in an EPP calculation where the annual GWP is discounted. While it appears methodologically consistent to apply a discount rate in an EPP calculation to an undiscounted GWP value representing annual emissions, LCA practitioners should (1) recognize that annual GWPs used in EPP calculations implicitly represent a multi-decadal timeframe, and (2) be wary of applying a discount rate both in the calculation of GWP itself as well as the EPP calculation, as this may understate the radiative effect of gases in the future.

Though altering the time horizon affects the GWP magnitude, the practical implications in this building-focused case study are small. In building operations, CH<sub>4</sub> comprises approximately 3% of global warming potential, while CO<sub>2</sub> comprises over 94%. However, the effect of GWP time horizon on EPP could have a large effect in other case studies. For example, consider a scenario where two buildings are compared, one of which produces more methane due to natural gas heating with upstream methane leakage. Changing from a 100-year timescale to a 20-year timescale would have a disproportionately larger effect on the natural gas building, which would affect its payback relative to the non-gas building it is compared against.

## **5 FUTURE WORK**

Based on the results of this study, further development of the EPP framework should be conducted to expand its utility in building project evaluation. Most beneficial would be the development of a parameterized model that can be applied to potential projects, rather than retrospective case studies, by integrating relevant LCA database information within the EPP framework. This would streamline the inventory for the primary impact-contributing materials and enable quicker EPP estimation. Alternatively, such a tool could be integrated with other building design or LCA tools (e.g. Revit, ATHENA Eco-Calculator) to make LCA more accessible for building project decision-making (Athena, 2011; Autodesk, 2018). Further quantitative exploration of demolition-related impacts including material end-of-life and recycling methods would improve upon the existing framework. Additionally, applications for building renovations could be explored, but would require higher resolution data on specific equipment-related impacts and estimated performance improvements from such renovations.

### **5.1 Role of Demolition and Recycling Methods**

Demolition impacts, though not included in the calculation of EPP, warrant further discussion and evaluation. Numerous building LCA studies have referenced impacts from demolition activities as minor compared to the rest of the building life cycle and instead focused on material end-of-life in building evaluation (Cabeza et al., 2014; Coelho & De Brito, 2012; Scheuer et al., 2003) though demolition is accounted for in some cases (Blengini, 2009). With respect to EPP, however, consideration must be given to how to distribute demolition impacts between existing and new buildings. There are several options. First, demolition-related impacts can be excluded because the existing building will eventually be demolished, and thus the building replacement does not create any additional demolition-related impacts.

Second, only impacts associated with early demolition and thus the truncation of existing building lifetime are accounted for. In this case, the demolition-related impacts can be calculated and allocated to the new building project based on the percentage of anticipated lifetime by which the existing building lifetime is shortened. Another method to account for early demolition entails calculating demolition impacts at the present time, and at the time at which the existing building is expected to reach the end of its useful life. In this case, the demolition allocated to the new building is the difference between these discounted impacts. Third, demolition can be entirely attributed to the new building, as the lifetime and end-of-life of the existing building is unknown, but the act of demolition is a consequence of the decision to replace the building. These impacts would be incorporated into the EPP calculation similar to the inclusion of construction-related impacts. However, demolition impacts are expected to be small (Kofoworola & Gheewala, 2008), thus having a minor effect on the results presented here.

Coupled with demolition is the disposal of materials and the end-of-life treatment of buildings. Much of building demolition debris is considered inert waste, and modern technologies have enabled the reuse and recycling of over 90% of non-hazardous building materials in demolition (Davis, 2017). Conventional demolition processes give less consideration to sorting and reuse of materials when removing a building, though selective demolition, also referred to as deconstruction, involves a more refined disassembly of the building and salvaging of materials for reuse and recycling. Sára et al (2001) worked to create an information system for decision-making with respect to demolition activity and the recovery, reuse, and recycling of waste, referred to as “valorization”. They assess demolition processes and waste transport, as well as waste recovery, treatment, or disposal in Italy. The

work highlights the value of reuse for both energy and material savings, through Coelho and De Brito (2012) state that those benefits can be eliminated if travel distances between site and point of reuse are too large.

In LCA, there are two common means of accounting for material recycling, the end-of-life recycling approach and the recycled content approach. End-of-life recycling credits the system for recycled content at disposal and assumes recycling is driven by the supply of secondary material. This is in contrast to the recycled content method, in which systems are credited for the initial incorporation of recycled material during production, and products only incur the impacts directly associated with them. Buildings may receive less environmental benefit from the recycled content approach than end-of-life recycling as materials that are recycled at building end-of-life are not necessarily reused in building applications.

Future versions of the EPP model could more closely consider building material end-of-life. Impact credits achieved through reuse and recycling could shorten EPP for many, if not all, impact categories, depending on allocation of demolition between buildings. If the net effect of demolition, reuse, and recycling is a decrease in impacts, attribution of demolition impacts to the new building would decrease EPP, while attribution of demolition to the existing building would increase EPP as the existing building would receive the recycling and avoided product credits.

## **5.2 Consideration of Renovation and New Construction**

This study attempts to quantify and evaluate EPP for new construction to offer a tool to aid decisionmaking when new construction is under consideration. This should not imply that new construction is the only option for building performance improvements. Performance-wise, energy reduction is a primary motivation for building replacement. Results indicated that

a 50% energy reduction in the new building compared to the old building would reduce EPP to 25 years or less for all impact categories. However, reductions can also be achieved through renovation.

Previous work has quantified potential energy and impact reductions for various renovation projects. Juan et al. (2010) developed a decision support system for building renovation to identify renovation opportunities for HVAC and lighting and generate implementable solutions. Over a 20 year period, their models estimated 39 to 43% reduction in energy consumption, life cycle energy cost, and CO<sub>2</sub> emissions. Other energy conservation measures that have been explored include installation of sun protection to reduce cooling loads by 8 to 35.5% with an average saving potential of 28% (Papadopoulos, Theodosiou, & Karatzas, 2002), and insulation improvements to produce a 41 to 88% reduction in heating consumption (Užšilaityte & Martinaitis, 2010). On the other hand, energy efficiency technologies applied to new commercial buildings can produce savings as high as 40% for some building types, but 20 to 30% on average (Kneifel, 2010).

These studies imply that, performance-wise, renovation savings could be comparable to new buildings, though some of these studies report values for target reductions such as heating and cooling, not total energy consumption. However, the renovations considered are major, not simply the implementation of energy conservation measures. These studies also suggest that achieving a 50% energy reduction between an existing and new building may be optimistic in many cases, thus it may be difficult to reduce EPP to less than 25 years for all impact categories. Impacts associated with renovation projects are likely to be lower overall compared with new building construction. Due to the shorter remaining building lifetime post-renovation,

renovation projects may need to have even shorter EPPs to be considered viable based on this metric.

### **5.3 Changes to Annual Energy Reduction**

To consider changes to energy efficiency and operational energy use, the methodology used in this EPP model could be refined. An alternative approach is to implement changes to the percent energy reduction at various points in the time horizon, generating a piecewise function for the existing building cumulative impact function. For example, if the new building is designed to consume 25% less energy than the existing building, but the existing building implements an energy conservation measure that reduces energy use by 5% in a later year, the slope of the cumulative impacts for the existing building would lessen to account for this change. Additionally, the net performance of the new building after the change would be 20%, and the model would use this difference for the subsequent years evaluated. This approach could be helpful in estimating EPP when comparing options for renovation versus new construction.

## **6 CONCLUSION**

The findings in this thesis indicate that it is environmentally advantageous to replace an existing building when the new building produces high energy savings when compared to the existing building, and when environmental impacts are evaluated using a low discount rate. Additionally, displacement of dirtier fuels when constructing a more energy efficient building further improves EPP. All ten impacts from the EPA TRACI impact assessment methodology are evaluated, and the sensitivity of each impact to building-related changes vary. A key indicator of sensitivity to energy reduction and discount rate is the ratio of initial construction impacts to annual operational savings. Impacts with higher ratios are more sensitive to changes,

while lower ratios are less sensitive. EPP values range widely (i.e., less than a decade to over a century) by both impact category and specified parameters, but base case conditions indicate EPPs between 7 and 50 years. Thus the time horizon and preferred impacts for reduction will govern whether or not building replacement is truly advantageous for the entity considering the project.

Results also lend themselves to a critique of the prevailing focus on operational impacts in building LCA. The exclusion of construction and material-related impacts does not fully capture impacts associated with building replacement. Operational impacts should be targeted for impact reduction, but inclusion of construction-related impacts is necessary to inform project decision making.

As a metric, EPP can help characterize the relative benefits between existing and new construction. By adapting the familiar principle of payback period, EPP translates environmental impact assessment into a common language that does not require the navigation of various impact units or LCA jargon. It can thus serve as one of many tools to aid in project decision making.

## REFERENCES

- Almansa, C., & Martínez-Paz, J. M. (2011). What weight should be assigned to future environmental impacts? A probabilistic cost benefit analysis using recent advances on discounting. *Science of the Total Environment*, 409(7), 1305-1314.
- Athena. (2011). Athena EcoCalculator. Retrieved from <http://www.athenasmi.org/our-software-data/ecocalculator/>
- Autodesk. (2018). Revit: Built for building information modeling. Retrieved from <https://www.autodesk.com/products/revit/overview>
- Bare, J., Young, D., Qam, S., Hopton, M., & Chief, S. (2012). Tool for the reduction and assessment of chemical and other environmental impacts (TRACI). *Washington, DC: US Environmental Protection Agency*,
- Bergsdal, H., Bohne, R. A., & Brattebø, H. (2007). Projection of construction and demolition waste in Norway. *Journal of Industrial Ecology*, 11(3), 27-39.
- Biswas, W. K. (2014). Carbon footprint and embodied energy consumption assessment of building construction works in Western Australia. *International Journal of Sustainable Built Environment*, 3(2), 179-186.
- Blengini, G. A. (2009). Life cycle of buildings, demolition and recycling potential: A case study in Turin, Italy. *Building and Environment*, 44(2), 319-330.
- Cabeza, L. F., Rincón, L., Vilariño, V., Pérez, G., & Castell, A. (2014). Life cycle assessment (LCA) and life cycle energy analysis (LCEA) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, 29, 394-416.
- Coelho, A., & De Brito, J. (2012). Influence of construction and demolition waste management on the environmental impact of buildings. *Waste Management*, 32(3), 532-541.
- Cuong, N. B., Bonsang, B., Lambert, G., & Pasqueir, J. L. (1975). Residence time of sulfur dioxide in the marine atmosphere. *Pure and Applied Geophysics*, 113(1), 489-500.
- Davis, C. (2017). Nearly all of NC State's Harrelson Hall recycled, salvaged. Retrieved from <https://sustainability.ncsu.edu/blog/2017/02/01/harrelson-hall-recycled-salvaged/>
- Ding, T., & Xiao, J. (2014). Estimation of building-related construction and demolition waste in Shanghai. *Waste Management*, 34(11), 2327-2334.
- Dreyer, L. C., Niemann, A. L., & Hauschild, M. Z. (2003). Comparison of three different LCIA methods: EDIP97, CML2001 and Eco-Indicator 99. *The International Journal of Life Cycle Assessment*, 8(4), 191-200.

- EIA. (2018). How much energy is consumed in U.S. residential and commercial buildings? Retrieved from <https://www.eia.gov/tools/faqs/faq.php?id=86&t=1>
- Energy Information Administration. (2017). *Annual Energy Outlook 2017: Electric power projections by electricity market module region..* Washington, D.C.: U.S. Department of Energy.
- EPA. (2016). Green building: Basic information. Retrieved from <https://archive.epa.gov/greenbuilding/web/html/about.html>
- EPA. (2017a). *Regulatory impact analysis for the review of the Clean Power Plan: Proposal.* Research Triangle Park, NC:
- EPA. (2017b). Understanding global warming potentials. Retrieved from <https://www.epa.gov/ghgemissions/understanding-global-warming-potentials>
- European Commission Joint Research Centre. (2010). *International Reference Life Cycle Data System (ILCD) handbook* (1st ed.). Luxembourg: Publications Office of the European Union.
- Faludi, J., & Lepech, M. (2012). Ecological payback time of an energy-efficient modular building. *Journal of Green Building*, 7(1), 100-119.
- Fleurbaey, M., & Zuber, S. (2012). Climate policies deserve a negative discount rate. *Chi.J.Int'L L.*, 13, 565.
- Gibbs, H. K., Johnston, M., Foley, J. A., Holloway, T., Monfreda, C., Ramankutty, N., & Zaks, D. (2008). Carbon payback times for crop-based biofuel expansion in the tropics: The effects of changing yield and technology. *Environmental Research Letters*, 3(3), 034001.
- Green Building Alliance. (2016). Green building certifications, rating systems, and labels. Retrieved from <https://www.go-gba.org/resources/building-product-certifications/>
- Hellweg, S., Hofstetter, T. B., & Hungerbuhler, K. (2003). Discounting and the environment should current impacts be weighted differently than impacts harming future generations? *The International Journal of Life Cycle Assessment*, 8(1), 8.
- Henry, A., & Frascaria-Lacoste, N. (2012). Comparing green structures using life cycle assessment: A potential risk for urban biodiversity homogenization? *The International Journal of Life Cycle Assessment*, 1-2.
- Holmgren, M., Kabanshi, A., & Sörqvist, P. (2017). Occupant perception of “green” buildings: Distinguishing physical and psychological factors. *Building and Environment*, 114, 140-147.

- International Organization for Standardization. (2006a). Environmental management -- life cycle assessment -- principles and framework (ISO 14040:2006). Retrieved from <https://www.iso.org/standard/37456.html>
- International Organization for Standardization. (2006b). Environmental management -- life cycle assessment -- requirements and guidelines (ISO 14044:2006). Retrieved from <https://www.iso.org/standard/38498.html>
- Jonker, J. G. G., Junginger, M., & Faaij, A. (2014). Carbon payback period and carbon offset parity point of wood pellet production in the Southeastern United States. *GCB Bioenergy*, 6(4), 371-389. 10.1111/gcbb.12056 Retrieved from <http://dx.doi.org/10.1111/gcbb.12056>
- Juan, Y., Gao, P., & Wang, J. (2010). A hybrid decision support system for sustainable office building renovation and energy performance improvement. *Energy and Buildings*, 42(3), 290-297.
- Kneifel, J. (2010). Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. *Energy and Buildings*, 42(3), 333-340.
- Kofoworola, O. F., & Gheewala, S. H. (2008). Environmental life cycle assessment of a commercial office building in Thailand. *The International Journal of Life Cycle Assessment*, 13(6), 498.
- Levasseur, A., Lesage, P., Margni, M., Deschênes, L., & Samson, R. (2010). Considering time in LCA: Dynamic LCA and its application to global warming impact assessments. *Environmental Science & Technology*, 44(8), 3169. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/20302334>
- Lu, L., & Yang, H. X. (2010). Environmental payback time analysis of a roof-mounted building-integrated photovoltaic (BIPV) system in Hong Kong. *Applied Energy*, 87(12), 3625-3631.
- Mukhopadhyay, J., Baltazar, J., Kim, H., & Haberl, J. (2011). Comparison of ASHRAE Standard 90.1, 189.1 and IECC codes for large office building in Texas. Energy Systems Laboratory, Texas A&M University.
- National Institute of Building Sciences. (2017). High performance building council. Retrieved from <https://www.nibs.org/?page=hpbc>
- Newsham, G. R., Mancini, S., & Birt, B. J. (2009). Do LEED-certified buildings save energy? Yes, but.... *Energy and Buildings*, 41(8), 897-905.
- Papadopoulos, A. M., Theodosiou, T. G., & Karatzas, K. D. (2002). Feasibility of energy saving renovation measures in urban buildings: The impact of energy prices and the acceptable pay back time criterion. *Energy and Buildings*, 34(5), 455-466.

- Peng, C. (2016). Calculation of a building's life cycle carbon emissions based on Ecotect and Building Information Modeling. *Journal of Cleaner Production*, 112, 453-465.
- Peng, J., Lu, L., & Yang, H. (2013). Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. *Renewable and Sustainable Energy Reviews*, 19, 255-274.
- Plumer, B., & Popovich, N. (2017, October 10,). How will the clean power plan repeal change carbon emissions for your state? *The New York Times* Retrieved from <https://www.nytimes.com/interactive/2017/10/10/climate/clean-power-plan-emissions-your-state.html>
- Ryberg, M., Vieira, M. D., Zgola, M., Bare, J., & Rosenbaum, R. K. (2014). Updated US and Canadian normalization factors for TRACI 2.1. *Clean Technologies and Environmental Policy*, 16(2), 329-339.
- Sára, B., Antonini, E., & Tarantini, M. (2001). Application of life-cycle assessment (LCA) methodology for valorization of building demolition materials and products. Paper presented at the *Environmentally Conscious Manufacturing*, 4193 382-391.
- Saunders, C. L., Landis, A. E., Mecca, L. P., Jones, A. K., Schaefer, L. A., & Bilec, M. M. (2013). Analyzing the practice of life cycle assessment. *Journal of Industrial Ecology*, 17(5), 777-788. 10.1111/jiec.12028 Retrieved from <http://onlinelibrary.wiley.com/doi/10.1111/jiec.12028/abstract>
- 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.
- Seo, S., & Hwang, Y. (1999). An estimation of construction and demolition debris in Seoul, Korea: Waste amount, type, and estimating model. *Journal of the Air & Waste Management Association*, 49(8), 980-985.
- Seo, S., & Hwang, Y. (2001). Estimation of CO2 emissions in life cycle of residential buildings. *Journal of Construction Engineering and Management*, 127(5), 414-418.
- Suh, S., Tomar, S., Leighton, M., & Kneifel, J. (2014). Environmental performance of green building code and certification systems. *Environmental Science & Technology*, 48(5), 2551-2560.
- Suzuki, M., & Oka, T. (1998). Estimation of life cycle energy consumption and CO2 emission of office buildings in Japan. *Energy and Buildings*, 28(1), 33-41.
- Tan, R. B., & Khoo, H. H. (2005). An LCA study of a primary aluminum supply chain. *Journal of Cleaner Production*, 13(6), 607-618.

- The White House. (2015). Fact sheet: President Obama to announce historic carbon pollution standards for power plants. Retrieved from <https://obamawhitehouse.archives.gov/the-press-office/2015/08/03/fact-sheet-president-obama-announce-historic-carbon-pollution-standards>
- Thiel, C. L., Champion, 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.
- Thomsen, A., & van der Flier, K. (2009). Replacement or renovation of dwellings: The relevance of a more sustainable approach. *Building Research & Information*, 37(5-6), 649-659.
- Turner, C., & Frankel, M. (2008). Energy performance of LEED for new construction buildings. *New Buildings Institute*, 4, 1-42.
- U.S. Green Building Council. (2013). *LEED reference guide for Building Design and Construction v4*. Washington, D.C.: U.S. Green Building Council.
- Užšilaityte, L., & Martinaitis, V. (2010). Search for optimal solution of public building renovation in terms of life cycle. *Journal of Environmental Engineering and Landscape Management*, 18(2), 102-110.
- Vandenbroucke, M., Galle, W., De Temmerman, N., Debacker, W., & Paduart, A. (2015). Using life cycle assessment to inform decision-making for sustainable buildings. *Buildings*, 5(2), 536-559.
- Wang, E., Shen, Z., & Barryman, C. (2011). A building LCA case study using Autodesk Ecotect and BIM model.
- Weingartner, H. M. (1969). Some new views on the payback period and capital budgeting decisions. *Management Science*, 15(12), 607.
- Wu, Z., Yu, A. T. W., Shen, L., & Liu, G. (2014). Quantifying construction and demolition waste: An analytical review. *Waste Management (New York, N.Y.)*, 34(9), 1683-1692. 10.1016/j.wasman.2014.05.010 Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/24970618>
- Yeheyis, M., Hewage, K., Alam, M. S., Eskicioglu, C., & Sadiq, R. (2013). An overview of construction and demolition waste management in Canada: A lifecycle analysis approach to sustainability. *Clean Technologies and Environmental Policy*, 15(1), 81-91.
- Zuo, J., & Zhao, Z. (2014). Green building research—current status and future agenda: A review. *Renewable and Sustainable Energy Reviews*, 30, 271-281.

## APPENDIX

## Appendix A1 New Building Materials

Table A1. Materials included in representation of new building construction

Material	Quantity	Units
<b>Concrete Work</b>		
Gravel fill	310	cy
10 mil poly vapor barrier	18,396	sf
Concrete	1191.0	cy
6x6-10/10 wire mesh	35,406	sf
6x6-8/8 wire mesh	18,396	sf
Rebar	30	tons
<b>Masonry</b>		
Brick veneer	5853	sf
<b>Structural and Miscellaneous Metals</b>		
Structural steel	252	tons
Metal floor deck	32,262	sf
Metal roof deck	17,159	sf
<b>Windows</b>		
Glazing with aluminum framing	23,250	sf
<b>Roofing</b>		
80 mil TPO roofing over R30 insulation	17,214	sf
<b>Plumbing</b>		
UG waste and vent, 2"	121	lf
UG waste and vent, 3"	37	lf
UG waste and vent, 4"	557	lf
UG waste and vent, 6"	288	lf
UG waste and vent, 8"	47	lf
UG waste and vent, 10"	67	lf
AG SWV, 2"	1209	lf
AG SWV, 3"	226	lf
AG SWV, 4"	243	lf
AG storm, 4"	46	lf
AG storm, 6"	401	lf
Copper, 1/2"	706	lf
Copper, 3/4"	657	lf
Copper, 1"	126	lf
Copper, 2"	353	lf
Copper, 2 1/2"	180	lf
Copper, 3"	58	lf
<b>HVAC</b>		
Sheet metal	40,232	lbs
Reinforcements, supports, stiffeners	6,035	lbs
CHW pipe, 2"	30	lf
CHW pipe, 3"	160	lf
CHW pipe, 4"	110	lf

Refrigerated liquid pipe, 3/8"	58	lf
Refrigerated liquid pipe, 1/2"	41	lf
Refrigerant suction pipe, 5/8"	58	lf
Refrigerant suction pipe, 2/4"	41	lf
UG CHW pipe, 4"	119	lf
<b>Interior Finishing</b>		
Drywall	63,510	sf
Ceramic tile	2408	sf
Terazzo flooring	11,628	sf
Wood framing, 2 x 12	665	lf
Wood framing, 2 x 6	3,677	lf
Acoustic ceiling tiles	31,521	sf

## Appendix A2 Energy Consumption Data

**Table A2. Existing building annual electricity use**

<b>Year</b>	<b>Annual Electricity Use (kWh)</b>
2009	699,300
2010	815,000
2011	852,500
2012	898,000
2013	836,100

**Table A3. Existing building annual fuel oil use**

<b>Year</b>	<b>Annual Fuel Oil Delivered (gal)</b>
2007	12,063
2008	13,033
2009	5,584
2010	15,782
2011	15,781
2012	11,959
2013	5,948

**Table A4. New building monthly electricity use**

<b>Month</b>	<b>Electricity Use (kWh)</b>
15-Jan	98,800
15-Feb	120,400
15-Mar	108,600
15-Apr	78,200

15-May	77,700
15-Jun	89,000
15-Jul	97,800
15-Aug	109,800
15-Sep	105,500
15-Oct	111,500
15-Nov	100,300
15-Dec	108,000
16-Jan	110,700
16-Feb	108,000
16-Mar	110,900
16-Apr	85,100
16-May	80,100
16-Jun	113,200
16-Jul	95,500
16-Aug	124,200
16-Sep	115,800
16-Oct	120,200
16-Nov	116,700
16-Dec	107,300
17-Jan	130,400
17-Feb	107,700
17-Mar	113,900
17-Apr	119,000
17-May	101,600
17-Jun	119,200
17-Jul	113,300
17-Aug	115,700

### Appendix A3 AEO 2017 SERC Fuel Mix Data

**Table A5. Projected generation contributions by fuel type for SERC - AEO 2017 Reference**

<b>Generation Source</b>	<b>2016</b>	<b>2020</b>	<b>2025</b>	<b>2030</b>	<b>2035</b>	<b>2040</b>	<b>2045</b>	<b>2050</b>
Coal	35.20%	31.84%	30.59%	29.60%	26.88%	25.70%	24.55%	24.43%
Petroleum	0.38%	0.27%	0.24%	0.13%	0.12%	0.11%	0.10%	0.10%
Natural Gas	32.85%	31.11%	33.34%	34.52%	33.01%	34.06%	35.05%	35.23%
Nuclear	27.44%	29.35%	28.21%	27.36%	26.20%	25.65%	24.63%	23.76%
Pumped Storage/Other	-0.27%	-0.15%	-0.16%	-0.16%	-0.15%	-0.15%	-0.15%	-0.15%
Renewables	4.39%	7.58%	7.78%	8.55%	13.95%	14.62%	15.81%	16.62%
Distributed Generation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%

**Table A6. Projected generation contributions by fuel type for SERC - AEO 2017 Reference with CPP**

<b>Generation Source</b>	<b>2016</b>	<b>2020</b>	<b>2025</b>	<b>2030</b>	<b>2035</b>	<b>2040</b>	<b>2045</b>	<b>2050</b>
Coal	35.20%	31.41%	31.06%	26.01%	25.09%	23.76%	22.60%	21.63%
Petroleum	0.38%	0.26%	0.24%	0.12%	0.11%	0.10%	0.09%	0.09%
Natural Gas	32.85%	31.50%	32.26%	36.04%	33.49%	33.52%	33.54%	34.71%
Nuclear	27.44%	29.42%	28.60%	28.12%	26.99%	26.38%	25.43%	24.80%
Pumped Storage/Other	-0.27%	-0.15%	-0.16%	-0.16%	-0.15%	-0.16%	-0.16%	-0.17%
Renewables	4.39%	7.56%	7.99%	9.87%	14.47%	16.41%	18.49%	18.93%
Distributed Generation	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%