ADVANCING GREEN BUILDING RATING SYSTEMS USING LIFE-CYCLE ASSESSMENT

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Submitted to the Graduate Faculty of

The Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2015

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

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The aim of this research was to quantitatively analyze the potential ability of life cycle assessment (LCA) in combination with green building rating systems (GBRS), such as Leadership in Energy and Environmental Design (LEED), to reduce a building's environmental impacts, considering variations in climate, renewables, energy sources and economic aspects.

First, international variations in the energy use and associated environmental life cycle impacts were investigated. A reference Building Information Model (BIM) office building was developed and placed in 400 locations with changes to meet energy standards. LCA was then performed on all the buildings' energy consumption. The results varied considerably between the U.S. (394 ton CO_2 eq) and international (911 ton CO_2 eq) locations. Since GBRS are expanding internationally, energy source considerations for buildings should be considered with a particular suggestion of targeted goals reductions versus aggregated certifications.

Second, the BIM and LCA models were extended to include on-site renewable energy (wind and solar) and located in 25 locations around the world. An LCA and LCCA were performed to consider different energy sources including renewables and associated prices at each site. Environmental impacts and economics varied dramatically. The requirements of renewable energy generation in existing GBRS need to be developed and changed to be a percentage of what is actually available on-site, instead of a fixed percentage of the building's energy.

Third, a comparative analysis was conducted for three whole-building LCA tools available today. The software tools vary in key aspects such as intended users, design stage, and time. One of the most important challenges is a comparison with a baseline. The results indicate that given the same building, the LCA results varied by about 10% in the pre-occupancy impact to 17% in the operational impact. This reinforces the need to not only refine LCA methods for GBRS, but also work towards robust data sets for building systems and products. At a minimum, GBRS should include LCA uncertainty analysis into their systems.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

AEC	Architecture, Engineering and Construction
ANSI	American National Standards Institute
ASHRAE	The American Society of Heating, Refrigeration and Air conditioning Engineers
AWWA	American Water Works Association
BEES	Building for Environmental and Economic Sustainability
BIM	Building information modeling
CAD	Computer-aided design
CSI	Construction Specifications Institute (CSI)'s MasterFormat
EIA	Energy Information Administration
Gal	Gallon
GBRS	Green Building Rating Systems
GBS	Autodesk Green Building Studio
GHG	Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating, Ventilating and Air Conditioning
IAQ	Indoor Air Quality
IESNA	Illuminating Engineering Society of North America

kBtu	Thousand British thermal units
kWh	Kilowatt hours
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LEED	Leadership in Energy and Environmental Design
Mcf	Thousand cubic feet of natural gas
MWH	Magee-Womens Hospital of UPMC
NREL	National Renewable Energy Laboratory
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
U.S. DOE	United States Department of Energy
U.S. EPA	United States Environmental Protection Agency
U.S. LCI	United States Life Cycle Inventory
UPC	Uniform Plumbing Code
UPMC	University of Pittsburgh Medical Center
USGBC	United States Green Building Council
VAV	Variable Air Volume
WHO	World Health Organization
WWAP	United Nations’ World Water Assessment Program

PREFACE

I would like to begin by acknowledging thanks to God Almighty, this work is the whole of his generosity and bounty. Praise be to God first and last. I would like to acknowledge the generous support of the Saudi Arabia government that made my PhD possible.

I would like to thank my advisor Dr. Melissa Bilec for her support and insightful suggestions throughout my PhD work. It has been a privilege to work under her guidance. Also, I would like to express my gratitude to committee members Dr. Vikas Khanna from University of Pittsburgh and Prof. Amy Landis from Clemson University. I was fortunate to have their suggestions that helped me to improve the quality of presented work.

I have been blessed with a family that has always been a source of love, inspiration, and encouragement to me. Their strong support enabled me to pursue my academic aspirations. I would like to express my deepest and most sincere thanks and love to my wife Sana, who is by the way started her PhD after me and finished it before me. Also, my kids Joanne, Ryan and Lara for their patience and cooperation during the research time. I would like to dedicate this dissertation to my parents who worked hard for me to be here.

1.0 INTRODUCTION

In recent years, climate change and energy consumption issues have garnered attention from policymakers and the public. As a result, regulations have been instituted and standards such as Green Building Rating Systems (GBRS) have been set requiring improvements in building energy and environmental performance. According to information released from the U.S Department of Energy, in the United States, buildings are responsible for more than 41% of the overall nonrenewable energy consumption and 40% of CO_2 emissions, with projections that those numbers will grow even higher in the coming years (US EIA 2012). Globally, buildings consume about one third of total energy use (IEA 2010c).

Fossil fuel dependency has led to an energy crisis that is deeply interlinked with environmental problems. CO_2 emissions are expected to increase in the next 25 years from the building sector, faster than any other sector, because commercial building projects are projected to grow the fastest, by 1.8% a year through 2030 (USGBC 2009). At the same time, potential mitigation opportunities exist as the International Energy Agency (IEA) predicts high-growth in renewable energy utilization in all sectors, with the highest increases in the building sector. By 2035, it is predicted that buildings will consume about 34% of final energy consumption (energy that can be delivered to consumers, e.g., electricity) from renewable sources (excluding traditional biomass) compared to 23% in the industrial sector and 15% in the transportation sector (IEA 2010a). Furthermore, in the next couple of years, renewables are expected to surpass natural gas as the second-largest source of power generation and by 2035 approach coal as the leading source (IEA 2013). Renewable energy will play a significant role in sustainable development through the achievement of these predictions. The extent of its role will depend on the priority placed on the relationship between renewable energy and sustainable development, which varies from one country to another depending on many domestic and international issues, such as social and economic development, energy access, energy security, climate change mitigation, reduction of environmental and human health impacts (Sathaye, Lucon et al. 2012). In the building design and construction industry, there are many programs and systems that support sustainable development by promoting increases in energy efficiency and incorporation of the use of renewables. Prominent rating systems include the Building Research Establishment Environmental Assessment Methodology (BREEAM) developed in the United Kingdom (BREEAM 2011), Green Star from Australia (GBCA 2010), the German Sustainable Building Council System (DGNB) from Germany (DGNB 2011), Estidama in the United Arab Emirates (Estidama 2012), the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) from Japan (IBEC 2010), and Leadership in Energy and Environmental Design (LEED) developed in the United States (USGBC 2006).

LEED is the most internationally recognized initiative providing a comprehensive third-party verification system for green buildings. Today, LEED has certified more than 10 billion square feet in buildings in more than 135 countries, making it the most commonly used rating system (USGBC 2013b). LEED was developed by the U.S. Green Building Council (USGBC) and has evolved through several versions, beginning with the pilot version in 1998 to the fourth version in 2013. LEED is currently the dominant green building rating system in the United States market and is being adapted to many markets worldwide (Fowler and Rauch 2006).

Although it was initiated in the US, it is now establishing its presence globally providing internationally adopted design, construction and operational guidelines and standards (Thilakaratne and Lew 2011). In fact, the LEED system has rapidly expanded into a global system that is utilized in most of the world. In 2013, about 4,900 cities with green building profiles were registered in the Green Building Information Gateway (GBIG), a USGBC data platform for green buildings (GBIG 2013). Moreover, 1.5 million square feet of building space get certified by LEED each day (USGBC 2013b). As of May 2013, the top ten countries by LEED certified/registered projects and gross square meters in millions (LEED Projects; GSM) are: the United States (44,270; 595.8), Canada (4,212; 62.3), China (1,156; 66.5), the United Arab Emirates (808; 46.1), Brazil (638; 18.1), India (405; 6.9), Mexico (322; 7.9), Germany (299; 6.1), Turkey (194; 8.9) and South Korea (188; 15) (USGBC 2013d).

1.1 MOTIVATION AND RATIONALE

Reduction in energy consumption is important to sustainable development since most currently used energy sources are becoming depleted and cause climate change. These concerns are in addition to the important economic and social concerns that vary around the world. However, reducing energy consumption does not necessarily reduce a building’s environmental impact at the same rate for all buildings. Applying Life-Cycle Assessment (LCA) to building rating systems at a systems level, especially rating systems targeting international markets, is critical to understanding and developing thoughtful and meaningful environmental reductions.

The current version of LEED is to a large extent based on energy models. LEED Energy and Atmosphere credits can be obtained by illustrating reductions in anticipated energy use via baseline models and design models. The accuracy of energy models is the subject of an ongoing debate. Some argue that the LEED rating system has lost some credibility in terms of energy efficiency, in part due to their reliance on model results (Turner and Frankel 2008). Another important issue is that two buildings in two different locations may obtain LEED EA credits by reducing energy consumption by 10% compared to their baselines while in fact they have large differences in actual environmental impact reduction because of other variables, of which electricity generation issues have been found to be the largest. Also, buildings may obtain credits by producing energy on-site, regardless of the type of energy and the ease of acquiring it at each site (Adalberth, Almgren et al. 2001).

At present, LEED has expanded to have a more comprehensive structure, with a global alternative compliance path that includes many subsystems (USGBC 2013c)..

1.2 RESEARCH AIM

The aim of this research is to quantitatively analyze the potential ability of green buildings rating systems, such as LEED, to reduce a building's environmental impacts in an international context, considering climate, energy sources and renewables. Recommendations for LEED were developed to necessitate buildings with higher environmental impacts to achieve higher levels of energy performance based on associated impacts instead of a current fixed percentage of improvement. The overall goal of this research is to promote greener buildings using life-cycle assessment (LCA) and systems thinking.

1.2.1 Research Questions

The following research questions are sequential in nature, tackling building energy use in question 1, then energy generation via renewables on-site in question 2. An integrated building information modeling (BIM) and life cycle assessment (LCA) model was developed in support of questions 1 and 2 and also used to answer question 3. Figure 1 depicts the building life-cycle process and delineates different stages of occupancy; it also shows the scope of each research question. The research questions are:

1. How can we better integrate LCA with GBRS like LEED to understand the variations in buildings' operational environmental impacts? How can we attain equitable certification with meaningful reductions of those impacts from a global perspective?
2. How can we advance GBRS using LCA to utilize the economic and environmental benefits of renewable energy internationally? How can we understand and model the potential for renewable energies in the context of building and systems-level impacts?
3. What are the current means available to designers to assess whole building LCA? What are the advantages and disadvantages of each of the tools and of employing them through GBRS?

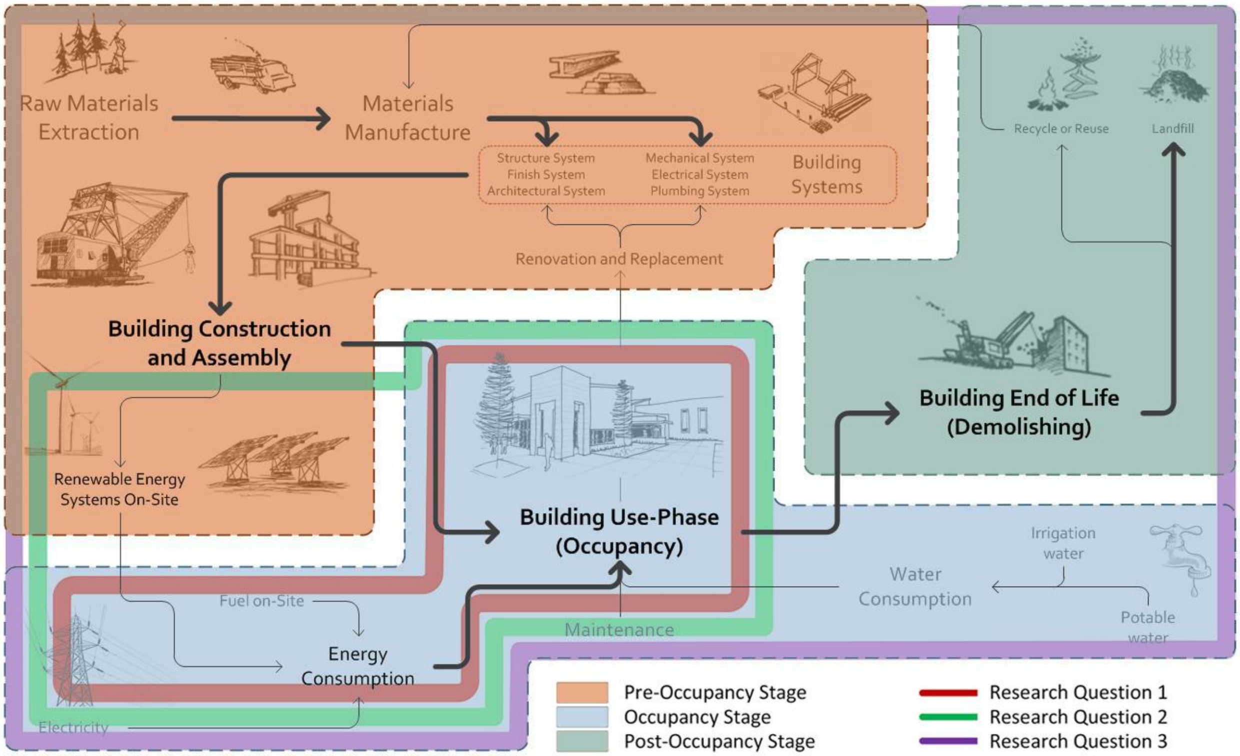


Figure 1. Building life cycle and the research questions scope

1.2.2 Research Objectives

The research objectives are:

A. Develop and test an integrated BIM and LCA model to investigate the variations in the environmental performance of buildings that represent different climatic and economic regions under LEED constraints. Identify advantages and limitations of the current LEED version and recommend improvements.

B. Investigate the variations in the economic and environmental benefits of on-site renewable energy in buildings to quantify tradeoffs between potential renewable utilization and the actual environmental impacts of the building. Develop recommendations for LEED to utilize the benefits of renewable energy using the perspective of life-cycle analysis.

C. Compare whole building LCA tools. Provide recommendations on whole building LCAs based on the results.

1.3 RESEARCH INTELLECTUAL MERIT

This dissertation advances GBRS through the application of life-cycle assessment. This research provides results and a structure for improving green building standards. First, it determines that LEED requirements for minimum energy performance and efficiency should be more strategic based on the fact that LCA results vary by location; buildings with higher environmental impacts should achieve higher levels of energy performance based on associated impacts instead of current fixed percentages of improvement. Second, requirements with respect to renewable energy generation on-site should be a percentage of what is actually obtainable on-site instead of current fixed percentages required for the building regardless of what is available on-site. Requirements also should consider the environmental performance of the building. Third, this work provides an approach of an integrated BIM and LCA model for whole building LCA. This approach will help designers to effectively demonstrate a reduction in the environmental impacts during the initial project decision-making.

1.4 ORGANIZATION OF DISSERTATION

Chapter 2 focuses on providing general background information about GBRS and other topics not included in the background sections in Chapters 3, 4, and 5; the other topics are GBRS with a focus on LEED, BIM, energy in buildings and envelope construction.

Chapter 3 addresses objective 1, which was to develop and test an integrated BIM/ LCA model to investigate the variations in the life-cycle environmental performance of buildings that represent different climatic and economic regions. This work was published in *Environmental Science & Technology* (Al-Ghamdi and Bilec 2015a) and *Proceedings of the 2014 International Conference on Sustainable Infrastructure* (Al-Ghamdi and Bilec 2014a).

Chapter 4 addresses objective 2, which was to investigate renewable energy potential in buildings using LCA and life-cycle costs on a system scale. This work is under review by *Environmental Science & Technology* and was published in *Proceedings of the 2014 International Symposium on Sustainable Systems and Technology (ISSST)* (Al-Ghamdi and Bilec 2014b).

Chapter 5 addresses objective 3, which was to perform a comparative analysis of the whole building life-cycle assessment using three tools that are currently available for analyzing buildings: Kieran Timberlake’s Tally, ATHENA’s Impact Estimator and PRé’s SimaPro. This work was published in *Proceedings of the 2015 International Symposium on Sustainable Systems and Technology (ISSST)* (Al-Ghamdi and Bilec 2015b) and *Proceedings of the 2015 International Conference on Sustainable Design, Engineering and Construction (ICSDEC)* (Collinge, Thiel et al. 2015). Conclusions and recommendations for future work are discussed in Chapter 6.

2.0 BACKGROUND

While there is robust research on individual topics in the areas of green buildings and LCA, minimal research was found that synthesized them at the systems level, which is a major contribution of this research. Therefore, the background section focuses on what is available in the research and on the individual topics.

Various LCA tools, standards, and rating systems have been developed to improve the environmental performance of buildings (see Chapters 3, 4, and 5 for additional information). Some of the tools and rating systems have been classified according to three levels. Level 3 is called ‘‘Whole building assessment framework or systems” and consists of methodologies such as BREEAM (UK), LEED (USA), and SEDA (Australia); level 2 is titled ‘‘Whole building design decision or decision support tools” and includes LISA (Australia), Ecoquantum (Netherlands), Envest (United Kingdom), ATHENA (Canada), and BEE (Finland); and level 1 is for product comparison tools and includes Gabi (Germany), SimaPro (Netherlands), and TEAM (France) LCAiT (Sweden) (Ortiz, Castells et al. 2009a). While these tools are available for use, limitations in these current environment assessment methods in buildings are prevalent.

On issue is if the tool is used by various users with different needs, the amount of required data may become too large, and often some compromises have to be made based on budget and time. Furthermore, updating the data is challenging due to the continual development of tools, processes and products (Haapio and Viitaniemi 2008). Several researchers have provided guidance for environmental assessment methods in buildings. For example, Haapio and Viitaniemi recommend a tool that provides alternatives (Haapio and Viitaniemi 2008). However, sustainability indicators in all building phases of design, construction, operations and dismantling need to be developed and used in order to target environmental and energy considerations worldwide (Ortiz, Castells et al. 2009a). Despite current shortcomings, GBRS and LCA are promising due to their market transformation potential and system analyses capabilities. The next section further describes the GBRS LEED.

2.1 GREEN BUILDING RATING SYSTEMS (GBRS)

GBRS are often voluntarily used design and management tools that are intended to promote more sustainable building design, construction and operation. GBRS can incorporate environmental concerns with economic benefits and other traditional decision criteria. Most GBRS have different subsets that cater to specific building projects, such as retrofits, new construction, commercial, residential, schools and healthcare facilities. Many countries develop their own rating system based on local and regional factors like the type of building stock, climate, and specific environmental concerns.

The individual circumstances of each country and region lead to the difficulty of creating a single global GBRS (Reed, Bilos et al. 2009). Prominent rating systems include the Building Research Establishment Environmental Assessment Methodology (BREEAM) developed in the United Kingdom (BREEAM 2011), Green Star from Australia (GBCA 2010), the German Sustainable Building Council System (DGNB) from Germany (DGNB 2011), Estidama in the

United Arab Emirates (Estidama 2012), the Comprehensive Assessment System for Built Environment Efficiency (CASBEE) from Japan (IBEC 2010), and Leadership in Energy and Environmental Design (LEED) developed in the United States (USGBC 2006). LEED is the most internationally recognized initiative to provide a comprehensive third-party verification system for green buildings. Today, LEED is used in more than 135 countries, making it the most commonly used rating system (USGBC 2013b).

LEED was developed by the U.S. Green Building Council (USGBC), evolving through several versions over the past twenty years, with the official launch of the pilot version, LEED v1.0, in 1998. This version targeted only new construction and new commercial office buildings. LEED then evolved continuously from the pilot version to LEED v2.0 in 2001; LEED v2.1 in 2003; LEED v2.2 in 2005; LEED 2009 in 2009 and finally LEED v4.0 in 2013. At present, LEED has expanded to have a more comprehensive structure, with a global alternative compliance path that includes many subsystems. Figure 2 shows its overall structure and includes the different specialized rating systems in both LEED 2009 and LEED v4. Those specialized rating systems are: Green Building Design & Construction (LEED BD+C), LEED Homes, Interior Design and Construction (LEED ID+C), Building Operations and Maintenance (LEED O+M), and finally, Neighborhood Development (LEED ND), which extends to areas beyond the building to include the surrounding community. These subsystems apply to both new buildings and major renovations of existing buildings and can be applied to many building types through even more specialized subsystems. For example, under LEED BD+C, the specialized subsystems include: New Construction, Core & Shell, Schools, Retail, Data Centers, Warehouses and Distribution Centers, Hospitality, Healthcare (USGBC 2013c).

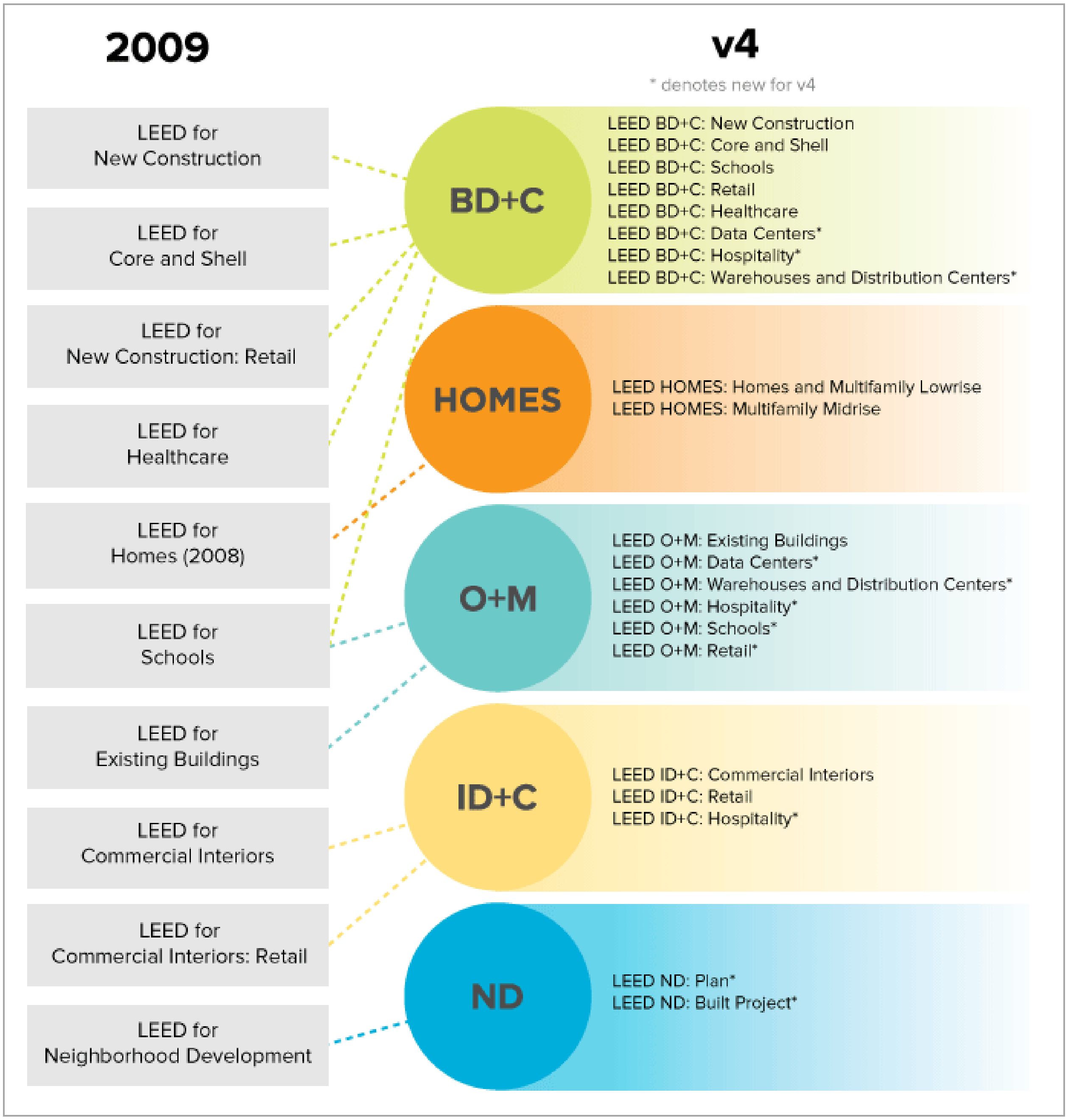


Figure 2. LEED 2009 and LEED v4 alignment
Chart adapted from U.S. Green Building Council (USGBC 2013c).

To understand how LEED works, an example is shown in Table 1. Table 1 shows a project checklist for new construction and major renovation under the LEED (BD+C) rating system. There are eight main categories that address different key issues. LEED (BD+C) for New

Construction and Major Renovation, water and materials contains eight categories: Location and Transportation; Sustainable Sites; Water Efficiency; Energy and Atmosphere; Materials and Resources; Indoor Environmental Quality; Innovation; Regional Priority; and finally, Integrative Process. Each category contains prerequisites that are mandatory and credits that will determine the certification level.

Table 1. LEED v4 for BD+C: project checklist for new construction and major renovation

Table adapted from U.S. Green Building Council (USGBC 2013c).

Location and Transportation		**16**
Credit	LEED for Neighborhood Development Location	16
Credit	Sensitive Land Protection	1
Credit	High Priority Site	2
Credit	Surrounding Density and Diverse Uses	5
Credit	Access to Quality Transit	5
Credit	Bicycle Facilities	1
Credit	Reduced Parking Footprint	1
Credit	Green Vehicles	1

Sustainable Sites		**10**
Prereq	Construction Activity Pollution Prevention	Required
Credit	Site Assessment	1
Credit	Site Development - Protect or Restore Habitat	2
Credit	Open Space	1
Credit	Rainwater Management	3
Credit	Heat Island Reduction	2
Credit	Light Pollution Reduction	1

Water Efficiency		**11**
Prereq	Outdoor Water Use Reduction	Required
Prereq	Indoor Water Use Reduction	Required
Prereq	Building-Level Water Metering	Required
Credit	Outdoor Water Use Reduction	2
Credit	Indoor Water Use Reduction	6
Credit	Cooling Tower Water Use	2
Credit	Water Metering	1

Energy and Atmosphere		**33**
Prereq	Fundamental Commissioning and Verification	Required
Prereq	Minimum Energy Performance	Required
Prereq	Building-Level Energy Metering	Required
Prereq	Fundamental Refrigerant Management	Required
Credit	Enhanced Commissioning	6
Credit	Optimize Energy Performance	18
Credit	Advanced Energy Metering	1
Credit	Demand Response	2
Credit	Renewable Energy Production	3
Credit	Enhanced Refrigerant Management	1
Credit	Green Power and Carbon Offsets	2

Materials and Resources		**13**
Prereq	Storage and Collection of Recyclables	Required
Prereq	Construction and Demolition Waste Management Planning	Required
Credit	Building Life-Cycle Impact Reduction	5
Credit	Building Product Disclosure and Optimization - EPD	2
Credit	Building Product Disclosure and Optimization - SRM	2
Credit	Building Product Disclosure and Optimization - MI	2
Credit	Construction and Demolition Waste Management	2

Indoor Environmental Quality		**16**
Prereq	Minimum Indoor Air Quality Performance	Required
Prereq	Environmental Tobacco Smoke Control	Required
Credit	Enhanced Indoor Air Quality Strategies	2
Credit	Low-Emitting Materials	3
Credit	Construction Indoor Air Quality Management Plan	1
Credit	Indoor Air Quality Assessment	2
Credit	Thermal Comfort	1
Credit	Interior Lighting	2
Credit	Daylight	3
Credit	Quality Views	1
Credit	Acoustic Performance	1

Innovation		**6**
Credit	Innovation	5
Credit	LEED Accredited Professional	1

Regional Priority		**4**
Credit	Regional Priority: Specific Credit	1
Credit	Regional Priority: Specific Credit	1
Credit	Regional Priority: Specific Credit	1
Credit	Regional Priority: Specific Credit	1

Credit	Integrative Process	**1**

TOTALS	**110**

- Certified: 40 to 49 points
- Silver: 50 to 59 points
- Gold: 60 to 79 points
- Platinum: 80 to 110 points

LEED certification involves four main steps: registration, application, review and certification. The procedures in each of those four steps change depending on the type of building and the type of rating system used. The following is a brief description of the overall LEED certification process (USGBC 2015b). In the first step, registration, the project team decides on a type of rating system (i.e. LEED BD+C or LEED O+M etc.) based on the project type and scope. During the registration process on LEED Online, the project team makes sure that the project meets all of the LEED Minimum Program Requirements (MPRs); otherwise they will not be able to register. MPRs represent the minimum characteristics that make a project appropriate for pursuing LEED. The MPRs are: comply with environmental laws; a complete, permanent building; use a reasonable site boundary; comply with minimum floor area requirements; comply with minimum occupancy requirements; commit to sharing whole-building energy and water usage data; comply with a minimum building area to site area ratio.

The second step (application) is where the project team collects and submits the appropriate documentation via LEED Online. In this step, the project team identifies LEED credits that can be achieved and submit appropriate documentation to support and to demonstrate the achievement. The third step (review) takes place after the project team has submitted an application and paid the review fee. At this stage, Green Business Certification Inc. (GBCI) conducts a thorough technical review. GBCI is the entity of USGBC responsible for LEED project certification. GBCI relies on reviewers from around the world, who actively engage with the project team throughout the review process. The review stage varies depending on the specific needs of the project and the rating system under which the project applied. In general, there are three phases of the review: preliminary review; final review (optional); and appeal review (optional, appeal fees apply). In some rating systems like BD+C and ID+C projects, the project team can apply for a split review, where the project can be reviewed at two stages: the design stage and the construction stage. The fourth step,, certification, the project may be certified at four different levels. LEED certified (40-49 points), Silver (50-59 points), Gold (60-79), and Platinum (80-110 points) (USGBC 2015a).

2.2 BUILDING INFORMATION MODELING (BIM)

As indicated in Section 2.1, understanding energy use in buildings is a key component in GBRS. One mechanism to begin to understand building energy use is through the integration of BIM and building energy models. This section further describes BIM.

BIM is the system of production and management of a building’s data during its life cycle (Lee, Sacks et al. 2006). BIM models, unlike Computer-Aided Design (CAD) models, manage not just graphics, but also information. BIM is essentially a 3-D model of a building with the added dimensions of time and cost. BIM began in the late 1980s, but it was not used as a tool for meeting sustainability objectives in building projects until the green building revolution in 1998. The Bureau of Economic Analysis reports that the architecture, engineering, and construction (AEC) industry is the largest industry in the United States, yet it is often acknowledged as a low-technology and inefficient industry, which has made initial penetration of BIM into this industry challenging (Gallaher, O’Connor et al. 2004). In a 2009 study, while BIM was available and had the ability to allow the interchange of object information between design and estimating software, automating the estimations, or at least the quantity takeoff process, was only done in special circumstances (Kraus, 2009). This is still true today.

To broaden the use of BIM three areas need to be investigated: new governance structures for projects that can support a more global construction industry; better integrated delivery of construction; and enhanced sustainability through new approaches, methods, and information technology (Levitt, 2007). Studies relating to sustainability can be divided into two groups – energy and water models and material estimating (Maile, 2009; Malkin, 2006 & Stadel, A., J. Eboli, et al. 2011).

The first category focuses on energy and water simulation. BIM makes it easier for a designer to perform energy and water simulations early in the design phase. There are several tools, such as E-Quest, Energy-Plus, and Green Building Studio, that can directly or indirectly integrate simulations with BIM models. Problems exist, however, and are being analyzed by some researchers. For instance, current seamless data import of building geometry data into energy simulation tools has limitations and usually includes either a process of iteratively changing the architectural model or manual checking and fixing of the partially converted geometry. There are typical and frequently encountered problems with data exchange related to building energy performance simulation (Maile, 2009). The second group of studies is related to materials and material reductions. Since BIM automates the types and the quantities of the materials of the models easily and quickly, reduction in waste due to material ordering and rework due to clashes is possible (Malkin, 2006). BIM plug-ins such as GBS or IESVE offer ‘black-box’ results. The estimates of fuel and electricity consumption from GBS or IESVE could be inputs for a use-phase analysis in SimaPro (Stadel, A., J. Eboli, et al. 2011).

2.3 ENERGY IN BUILDINGS

Overall, 39% of the energy in the US is consumed by buildings. Additionally, the use phase of buildings accounts for 71% of the total electricity consumption in the US (US EIA 2012). Depending on the building type, Heating Ventilation and Air Conditioning (HVAC) systems are responsible for 10–60% of the total building energy consumption (Trčka, L.M. Hensen et al. 2010). HVAC systems play an important role not only in ensuring occupant's comfort and preserving air quality, but also in allowing the optimization of a building' energy consumption (Nassif and Moujaes 2008). Therefore, improvements in the HVAC system have the potential to significantly reduce overall energy consumption in buildings.

The energy efficiency of HVAC systems can be improved in multiple ways. For example, the choice of materials chosen for the building can change the annual heating and cooling demands for a building from 7.81 kWh/ft^2 to 0.93 kWh/ft^2 (heating) and from 5.41 kWh/ft^2 to 3.94 kWh/ft^2 (cooling) (Khodakarami, Knight et al. 2009). Operating technology or strategy is another way to increase the energy efficiency of the HVAC system. For instance, through a strategy of determining the set points of local-loop controllers used in a multi-zone HVAC system, the energy consumption can be reduced by about 11 percent (Nassif and Moujaes 2008). Moreover, a single-objective optimization model applied in the operation of the HVAC system can help to optimize a 7.66% savings of the total energy in spite of an energy increase in certain individual components (Kusiak, Li et al. 2011). Instead of considering the whole HVAC system for ways to improve energy efficiency, some studies focus on specific areas of HVAC system. For instance, ventilation strategies have been examined independently by Olli Seppänen. Seppänen asserts that strategies such as banning smoking indoors, employing high efficiency air distribution, and balancing air flows can improve the energy efficiency of the ventilation system while at the same time improving indoor air quality (Seppänen 2008).

2.3.1 Envelope Construction

A building envelope is the physical separator between the interior and the exterior environments of a building. The insulation within the envelope is the primary factor in the reduction of heat transfer between the interior and exterior of the building. Thirty years after the introduction of compulsory thermal insulation in most European countries, insulation materials are still the major tool for determining a building's energy behavior (Papadopoulos 2005). Therefore, the proper design and selection of a building envelope and its components can also contribute to reducing the HVAC load. For example, thermal insulation helps in extending periods of thermal comfort without reliance on mechanical air-conditioning, especially during inter-season periods (Al-Homoud 2005). In Sweden, in order to increase the energy efficiency of the buildings the requirement of thermal insulation thickness for the walls increased from 130 mm in 1982 to 240 mm in 1999, and the thermal insulation thickness in roofs rose from 200 mm in 1982 to 450 mm in 1999 (Papadopoulos 2005).

For new building construction, there are many energy efficient insulation options that can be considered. In order to maximize energy efficiency, there is a whole-building system design approach which allows interaction between the insulation and the other building components. But for existing buildings, the thermal insulation is generally increased by adding insulation to the existing buildings' walls. Many types of insulation for walls exist, but the primary consideration for adding insulation to existing finished walls is using loose-fill or sprayed foam insulation (Energy Savers 2011). These two types of insulation can be added without much disturbance to finished areas.

2.4 SUMMARY

Overall this chapter presents background on GBRS and other topics like BIM and energy in building. The following chapters focus on specific areas in GBRS. For example, most of the work of Chapter 3 deals with the Energy and Atmosphere category, in particular the prerequisite (Minimum Energy Performance – EAP2) and credit (Optimize Energy Performance – EAC2) areas. The work in Chapter 4 also focuses on the Energy and Atmosphere category, but it focuses on the credits (Renewable Energy Production – EAC5) and (Green Power and Carbon Offsets – EAC7). Finally, the work in Chapter 5 addresses the Materials and Resources category, in particular, credit (Building Life-Cycle Impact Reduction – MRC1). The requirements of each prerequisite/credit is discussed in detail in each chapter. More detailed information on the development of the BIM, energy molding, and LCA model are presented in the Methods section of each chapter.

3.0 LIFE-CYCLE THINKING AND GBRS

The research presented in this chapter addresses research Objective A. Specifically, it answers the questions ‘How can we better integrate LCA with GBRS like LEED to understand the variations in buildings’ operational environmental impacts?” and “ How can we attain equitable certification with meaningful reductions of those impacts in the global context?”

This chapter and some of the introduction contain materials related to publications in *Environmental Science & Technology* (Al-Ghamdi and Bilec 2015a) and *Proceedings of the 2014 International Conference on Sustainable Infrastructure* (Al-Ghamdi and Bilec 2014a). The material appears here in accordance with the copyright agreement with American Chemical Society Publications and American Society of Civil Engineers. Supporting Information related to this chapter appears in Appendix A.

3.1 OVERVIEW

This chapter investigates the relationship between energy use, geographic location, life-cycle environmental impacts, and LEED. This chapter presents information about worldwide variations in building energy use and associated life-cycle impacts in relation to the LEED rating systems. A BIM model of a reference 43,000 ft^2 office building was developed and situated in

400 locations worldwide while making relevant changes to the energy model to meet reference codes, such as ASHRAE 90.1. Then life-cycle environmental and human health impacts from the buildings' energy consumption were calculated. The results revealed considerable variations between sites in the U.S. and international locations (ranging from 394 ton CO_2 eq to 911 ton CO_2 eq, respectively). The variations indicate that location specific results, when paired with life-cycle assessment, can be an effective means to achieving a better understanding of possible adverse environmental impacts as a result of building energy consumption in the context of GBRS. Looking at these factors in combination and using a systems approach may allow rating systems like LEED to continue to drive market transformation towards sustainable development while taking into consideration both energy sources and building efficiency.

3.2 INTRODUCTION AND BACKGROUND

Dependence on fossil fuels as primary energy sources has led to many energy crises and deeply interlinked environmental problems such as fossil fuels depletion and greenhouse gas (GHG) emissions. GHG emissions associated with the provision of energy services are a major cause of climate change. At the end of 2010, emissions continued to grow and CO_2 concentrations increased to over 39% above preindustrial levels (Edenhofer, Madruga et al. 2012). Among the three major contributors to GHG emissions (buildings, industry and transportation), buildings account for 41% of primary energy use and 40% of CO_2 emissions in the United States (US EIA 2012). It is projected that in the next 25 years, CO_2 emissions from the building sector will increase faster than any other sector. This projected increase is related to the growth of emissions from commercial buildings, which will increase by 1.8% per year through 2030 (USGBC 2009).

3.2.1 Life-Cycle Assessment and LEED

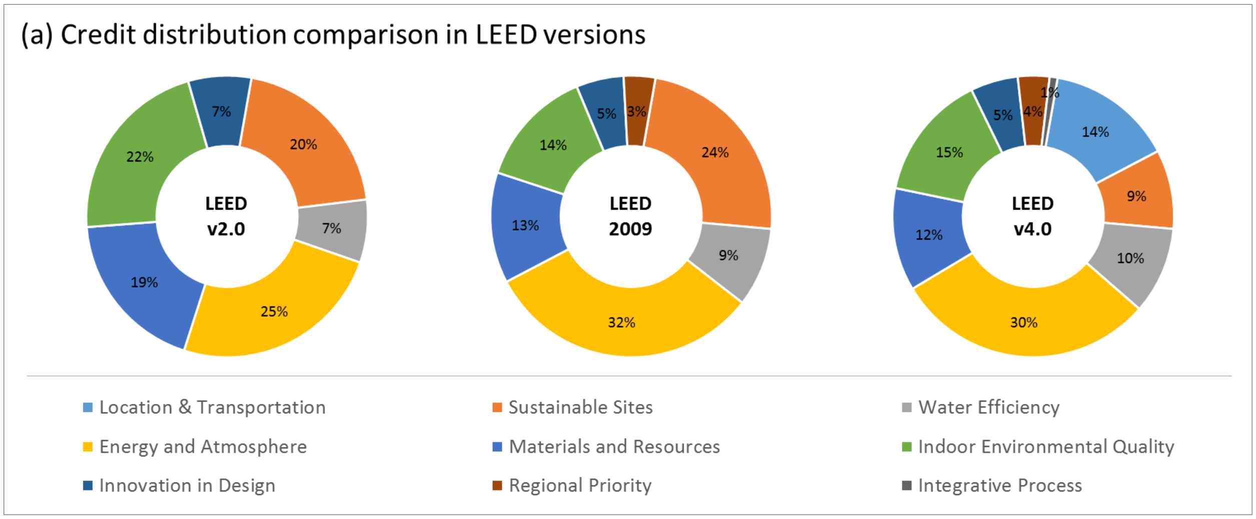
LCA is a method used to evaluate the environmental impacts of products and processes during their life cycle from cradle to grave (Blengini and Di Carlo 2010). LCA follows four steps formalized by the International Organization for Standardization (ISO), 14040 and 14044 (ISO 1997, ISO 2006). Identifying the goal and scope is the first step in LCA, where a system boundary is established and a functional unit for the system is defined. This stage is important because it establishes an equivalent comparison of the results. Life-Cycle Inventory (LCI) is the second step in LCA, where one can quantify the emissions associated with each input and output of the energy generation processes (the subject of this chapter) or any other processes. Life-Cycle Impact Assessment (LCIA) is the third step, where environmental impacts from the inputs and outputs of each process are calculated using various methods. Interpretation is the fourth step, where the significant findings or conclusions can be identified based on the results of the LCI and LCIA steps.

The use of LCA as an assessment tool in the building sector began in the early 1990's and its use has grown and expanded since its inception (Fava 2006). In the literature, some studies have explored LCA in buildings in various parts of the world (Ortiz, Castells et al. 2009b). Studies have also looked deeply into how to incorporate LCA in the development of LEED (Scheuer and Keoleian 2002, Humbert, Abeck et al. 2007). Growing interest in integrating LCA into building construction decision-making has grown as a result of its comprehensive and systems approach to environmental evaluation. Although the general LCA methodology is well defined, some argue that its application in the building industry still lacks sector-specific standardization and use, especially in the United States. In fact, most building LCAs are difficult to compare as they are based upon different boundaries and scopes (Blengini and Di Carlo 2010).

Discussions on LCA integration have appeared in many panels and working groups of the USGBC, beginning in 2006 (Trusty 2006). The 2009 version introduced a fundamental change in how LEED credits were ‘weighted.’ This weighting was adapted using LCA considerations. Weighting is a term used in the LCA community that essentially means a priority for some environmental categories over others. In the weighting scheme, building impacts are described with respect to 13 impact categories based on the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI) that was developed by the US Environmental Protection Agency (EPA). These impact categories were then compared to or weighted against each other according to Building for Environmental and Economic Sustainability (BEES), a tool developed by the National Institute of Standards and Technology (NIST) (Bare, Norris et al. 2002, Gloria, Lippiatt et al. 2007, USGBC 2008). The TRACI categories with relative BEES weightings adjusted for LEED are shown in Figure 3.

, Figure 3 also displays the changes in the LEED system due to the use of this weighting scheme by comparing all categories of LEED rating system v2.2 (2005), 2009, and v4.0. Given the significant impact of energy use and pressing climate concerns, the points for the Energy and Atmosphere category increased from 25% in 2005 to 32% in 2009, while those for most other categories decreased. LCA is both explicitly and implicitly incorporated into the current version of LEED (v4.0) given the prominence of Environmental Product Declarations (EPD). The category of Materials and Resources (MR) includes two sets of credits using LCA. First, the credit MR Building Life-Cycle Impact Reduction option 4 includes conducting a whole-building LCA and a minimum of 10% reduction from the baseline building in at least three impact categories, one of which must be global warming potential. The second LCA-related credit is MR Building Product Disclosure and Optimization – Environmental Product Declarations

(EPD), option one. EPDs are standardized documents intended to communicate life-cycle environmental impacts (USGBC 2013a).


(a) Credit distribution comparison in LEED versions

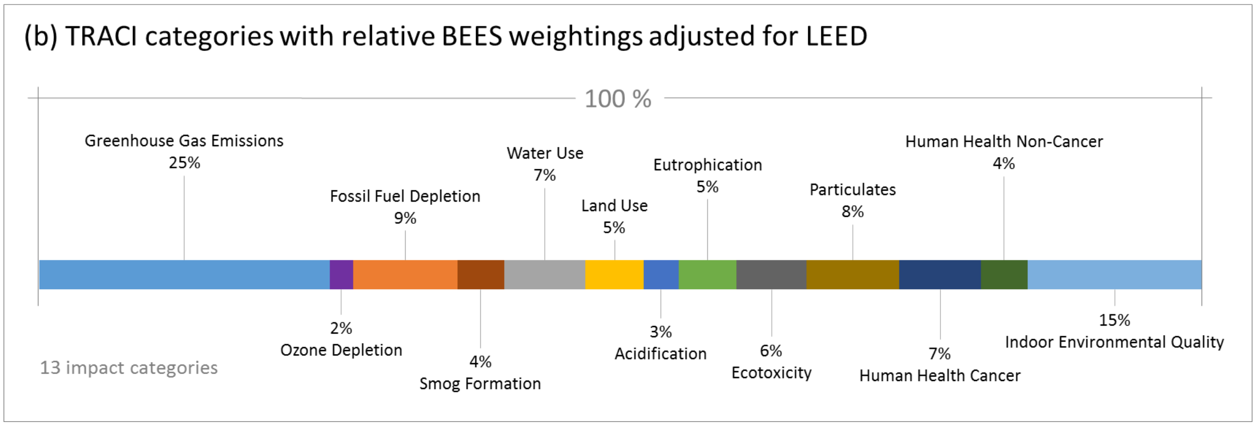

(b) TRACI categories with relative BEES weightings adjusted for LEED

Figure 3. Changes in LEED credit distributions over time. Panel (a) displays the changes in the credits distribution in LEED v2.0, LEED 2009, and LEED v4, using the weights and categories described in Panel (b). LEED v2.0 (2001) is the same in terms of credits distribution to the updated versions that followed, v2.1 (2002) and v2.2 (2005). In the LEED 2009 version, a new category (Regional Priority) was introduced. The current version of LEED v4.0 (2013) is relatively similar in weighting to the 2009 version. The category Location & Transportation was introduced largely from the Sustainable Sites category and a new category, Integrative Process, was introduced. TRACI = Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts; BEES = Building for Environmental and Economic Sustainability.

3.2.2 Motivation and Purpose

Reduction in energy consumption is critical because fossil fuels sources are being depleted and greenhouse gases are linked to fossil fuel production and use. However, reducing energy consumption does not necessarily reduce a building's environmental and human health impacts at the same rate for all buildings, especially since there are many important national and international differences in upstream energy production. That is, two buildings in two different locations may have vast differences in environmental performance due to many issues. An important issue, electricity mix, has been found to be one of the largest variables (Adalberth, Almgren et al. 2001). LEED requires buildings to demonstrate an improvement of a fixed percentage of savings beyond an energy reference standard (ASHRAE or approved equivalent), regardless of the source of energy or any other variables in the building site anywhere in the world. In this work, one aim is to show that applying LCA to building rating systems at a systems level, especially rating systems targeting international markets, is critical to understanding and developing thoughtful and meaningful environmental reductions.

The current version of LEED (v4.0) is, to a large extent, based on energy models. LEED Energy and Atmosphere credits can be primarily obtained by illustrating reductions in anticipated energy use via baseline models and design models. In this chapter, the same steps required by LEED have been followed to attain certification in 100 sites nationally within the United States and 300 sites internationally. The environmental and human health impacts from the energy use phase of each building were calculated using LCA. After examining the findings nationally and internationally, a set of potential recommendations for LEED to consider was developed, mainly focusing on the idea that buildings with higher environmental impacts achieve higher levels of energy performance based on associated impacts instead of requiring a fixed percentage of improvement as is currently the case.

3.3 MATERIALS AND METHODS

This chapter investigates environmental and human health impacts from building energy use in the context of green building rating systems such as LEED. Two major steps have been undertaken to achieve the study’s objectives. First, a representative case study building was developed and its energy consumption was calculated in 400 different locations. This case study building was modified to reflect local conditions like weather. Second, LCA was used to calculate the environmental and human health impacts at each location. The scope of the LCA was limited to the building operation/use phase because this phase represents the greatest environmental and human health impacts (70% to 90%) (Ortiz, Castells et al. 2009b). Additionally, the energy consumption in this phase represents 85% compared to the other phases of construction and demolition (Aktas and Bilec 2012). Evaluation and optimization of construction materials and processes using LCA are covered by the current version of LEED (v.4.0) in the category of Materials and Resources, which includes the phases of construction and demolition (USGBC 2013a).

3.3.1 Building and Energy Modeling

It is impractical to model every LEED building, or even to represent building types, characteristics and technologies, so a building type was selected as a reference building that could be placed in various locations with the necessary adjustments, such as achieving the R-value requirements. This practice is often used in studies, with perhaps the most notable work conducted by the U.S. DOE and its national laboratories, to serve as starting points for energy efficiency research (U.S. Department of Energy 2010). DOE reference buildings are used for several objectives like measuring the DOE energy efficiency goals for commercial buildings and evaluating the performance of energy codes such as ASHRAE (National Renewable Energy Laboratory 2011). The DOE reference building does not comply with LEED requirements, so it was not use it for this study. Instead, the reference case study building in this chapter was designed to meet LEED requirements based on the best publicly available data on commercial buildings from the Commercial Buildings Energy Consumption Survey (CBECS) (US EIA 2003). An example of this compliance is illustrated by LEED daylight requirements. LEED requires buildings to achieve a minimum glazing factor of 2% in a minimum of 75% of all regularly occupied areas. This factor represents the ratio of interior illuminance at a given point (September 21 and March 21) on the work plane to the exterior illuminance under known overcast sky conditions.

To determine the type and size of the reference building, the Public LEED Project Directory, which contains all buildings certified and registered by LEED and publicly available, was consulted (USGBC 2014). According to the directory, commercial offices are the largest building type certified by LEED and represent 29% of all certified buildings (excluding LEED for Homes). The median space of all certified office buildings is around 40,000 ft^2 (3,716 m^2) (USGBC 2014). Therefore, a standard reference building was designed using BIM that represents this most prevalent building type and the most prevalent characteristics. Using the reference building, energy models were generated for each location that represented fairly realistic buildings and typical construction practices. Table 2 illustrates the input data utilized to build the energy models at each location. These are hypothetical models with ideal operations that meet minimum LEED requirements.

Table 2. Building Energy Models - Input Categories, Description, and Data Sources

Input Categories	Description and Data Sources
Building Program: Building Type & Total Floor Area, Plug & Process Loads, Ventilation Requirements, Occupancy, Space Environmental Conditions, Domestic Hot Water (DHW), Operating Schedules	Building type and area were based on the LEED project directory (USGBC 2014). The total area is 43,000 ft^2 (4,000 m^2)1. All plug and process loads were based on the California 2005 Title 24 Energy Code (California Building Standards Commission 2005). Occupancy density and ventilation meet the ANSI/ASHRAE Standard 62.1 (ASHRAE, ANSI et al. 2007b). DHW was based on ANSI/ASHRAE/IESNA Standard 90.1 (ASHRAE, ANSI et al. 2007a). Operation schedules were set to be the same according to the local time and calendar of each location (local holidays and daylight savings were taken into account).
Building Form: Number of Floors, Aspect Ratio, Window Fraction, Window Locations, Shading, Floor Height, Orientation	All data on the building form were based on the 2003 Commercial Buildings Energy Consumption Survey (CBECS) (US EIA 2003). The building consisted of four floors with a total occupancy of 200 users. Floor height was 13 ft (4 m). Glazing target: windows 40%, skylight 5%; however, south/north facing percentages changed based on location (northern or southern hemisphere).
Building Fabric: Exterior Walls, Roof, Floors, Windows, Interior Partitions, Internal Mass, Infiltration	Substantially changed based on the climate zone in compliance with LEED requirements. All building materials that shape thermal characteristics were set to meet the minimum R-value requirements ANSI/ASHRAE/IESNA Standard 90.1 (ASHRAE, ANSI et al. 2007a).
Building Equipment: Lighting, HVAC System Types, Water Heating Equipment, Refrigeration, Component Efficiency, Control Settings	Constant in all sites; selections were determined based on the building type and meet the ANSI/ASHRAE/IESNA Standard 90.1 (ASHRAE, ANSI et al. 2007a). Lighting power density was 10.85 W/m2. Two ASHRAE baseline HVAC system types were used: System 5 and System 6, depending on the building type and size (clarifications mentioned below).

1. Building was designed at 43,000 ft^2 (4,000 m^2), slightly larger than the size of the LEED median building (40,000 ft^2)

Autodesk Green Building Studio (GBS) Version 2014.1.28.2302 (DOE-2.2-44e4) was utilized. It is an energy modeling tool that meets the LEED requirement for calculating a building's baseline performance according to ANSI/ASHRAE/IESNA Standard 90.1 (ASHRAE, ANSI et al. 2007a). A total of 400 independent energy models were developed in different locations worldwide. The number of sites per country varied according to the size of the economy and the geographical size of the country. Within these constraints, the sites were identified using simple random sampling among locations that contain urban clusters. In other words, none of these locations were situated in a rural or remote area, where such a building would be unlikely to exist. This selection process was designed to capture climatic and economic differences and to obtain better representation in the results. The total number of sites was 100 (25%) from the United States, 134 (34%) from the G-20 major economies, and 166 (42%) from the rest of the world. Only a few countries were not included in the study due to international sanctions (e.g., Iran and North Korea) and instability (e.g., Rwanda and Gambia).

As shown in Table 2, two ASHRAE baseline HVAC system types were used. Those types were determined based on the building type and size. The first type, System 5, is a packaged rooftop Variable Air Volume (VAV) that includes reheating, direct expansion cooling, and heating with a hot-water fossil fuel boiler. The second type, System 6, is similar to System 5 except in heating because it utilizes electric resistance (parallel fan-powered boxes). To determine which of the two systems would be used at each site, CBECS was used to identify the primary space-heating source by climatic zone and EIA statistics to confirm the presence of natural gas. Natural gas was used when available and when there was a significant heating load. All minimum requirements and baseline HVAC systems were utilized throughout the study in order to establish a comparable LEED baseline for each location in a standardized manner. Nonetheless, as it is impractical to model every technology available today, a common starting point was provided to measure the progress of LEED’s environmental performance while leaving the door open for solutions to mitigate environmental burdens using on-site or building integrated energy systems.

3.3.2 Life-Cycle Assessment (LCA)

LCA was used to analyze the environmental and human health impacts resulting from a building’s energy as consumed in different locations. A basic assumption was that each comparable component in the building, such as usable area, building layout and orientation, had the same design and functionality. The environmental impacts of energy consumption in each location were analyzed and the results compared to those of other locations.

Life-Cycle Inventory (LCI), as mentioned earlier, quantifies the emissions associated with each input and output of the energy generation process and does not account for transmission and distribution losses. The LCI unit processes were selected based on Ecoinvent database v2.2 (Frischknecht, Jungbluth et al. 2005). Electric power plant source data were collected for different sites: US plants from the US Environmental Protection Agency, EGRID 2006 Data and 2004 Plant Level Data (US EPA 2012); international sites from the 2009 Carbon Monitoring for Action (CARMA) database (CARMA 2009), and International Energy Agency (IEA) database for data not included in CARMA (IEA 2009). Also, IEA CO_2 emissions from fuel combustion data were used to adjust efficiency rates and emissions from different countries (IEA 2012). Figure 4 illustrates all electric power plant sources and associated locations.

Life-Cycle Impact Assessment (LCIA) characterizes the environmental impacts from the inputs and outputs of each unit process. ReCiPe impact assessment, originally developed in the Netherlands and used in most of today’s LCA software, was utilized(Goedkoop, Heijungs et al. 2009). In this chapter, three impact categories are focused on: climate change, human health, and water depletion. Climate change characterization factors are adapted with global warming potentials for a 100-year time horizon (Goedkoop, Heijungs et al. 2009).

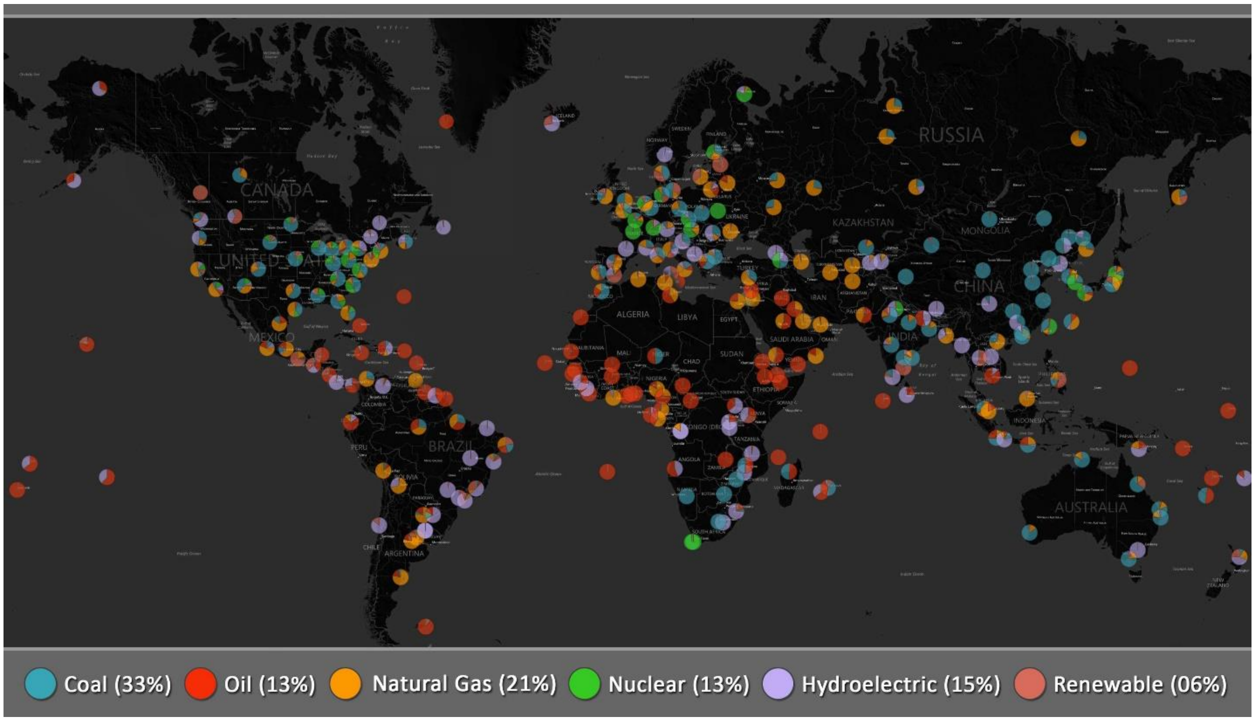


Figure 4. Distribution of the locations within the study according to power plant and energy sources (full data can be found in Appendix A page 91).

3.4 RESULTS AND DISCUSSION

Since the study sample included 400 sites, the main features of the analyzed data are first presented, focusing on two key issues: energy and economic performance, and then environmental and human health impacts. The respective results for each site can be found in Appendix A, Table 6 and Table 8. The limitations and applicability of the methods in this chapter are then addressed before presenting the conclusions.

3.4.1 Energy and Economic Performance

Variations in the results for energy consumption and economic performance were expected due to the variations in climate and energy costs in different parts of the world. ASHRAE classifies locations around the world according to thermal criteria into eight climate zones from 1 (Very Hot) to 8 (Subarctic) depending on the number of Cooling Degree Days (CDD) and Heating Degree Days (HDD), measurements designed to reflect the demand for energy needed to heat or cool a building. Also in each zone are three subtypes: A (Humid), B (Dry) and C (Marine). The reference building responded to these climatic conditions by applying LEED/ASHRAE requirements that change significantly from one climate zone to another. There will always be variations in the amount of energy consumed due to climatic variations. Figure 5 demonstrates energy consumption in 16 selected locations that represent the varying climate zones covered by the study. We can note considerable variation where the energy use intensity of the building in Brazil (zone 1A) was 58 (kBtu/ft^2/year) while the building in Russia (zone 8) was 128.5 (kBtu/ft^2/year). As the graph demonstrates, HVAC was responsible for this range, with other elements indicating minimal variation.

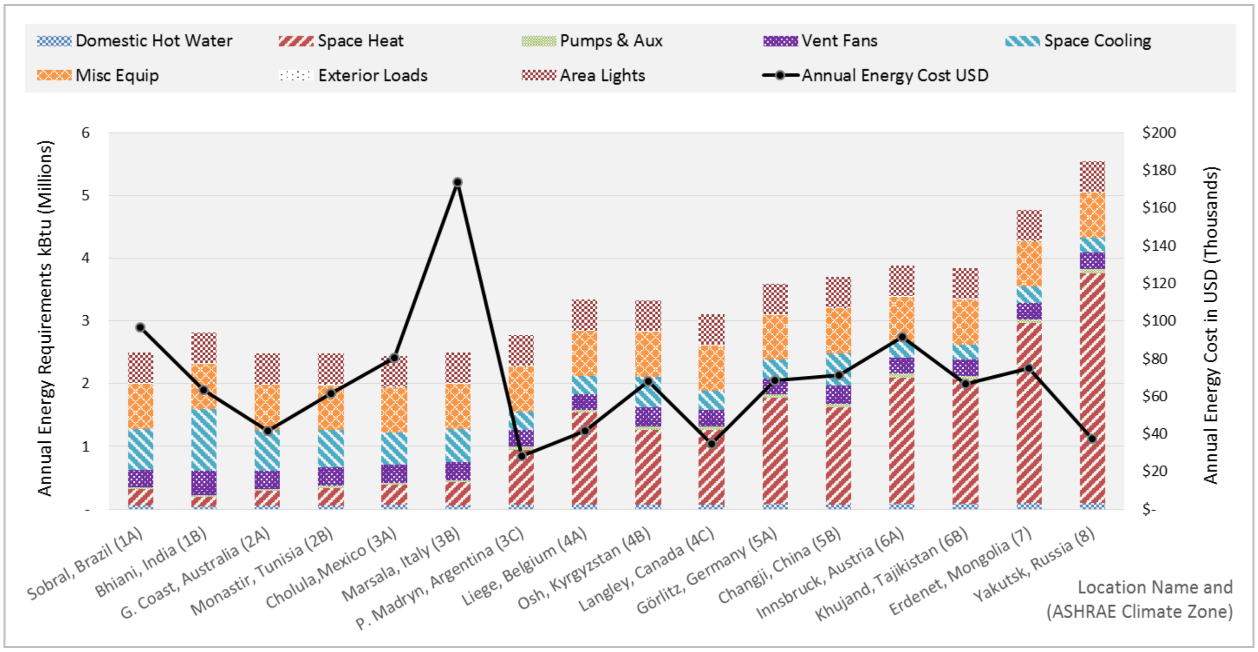


Figure 5. Annual energy consumption and cost in 16 selected locations representing different climate zones and economic conditions. Locations sorted by ASHRAE climate zone, from 1 on the left to 8 on the right. The stacked columns represent the annual energy requirement details at each site, referenced on the left in millions of kBtu. The black line with markers represents the annual energy cost at each site, referenced on the right in thousands of US dollars.

To examine the economic performance of the building under LEED constraints, it was necessary to also include the energy costs in the different locations. Utility rates often vary significantly from one location to another based on many local and regional variables; moreover, they also fluctuate considerably according to time of day and season and depending on supply and demand factors. For these reasons, the average retail price was used from EIA/IEA as of December 2011. In the 100 U.S. locations, the average rates for each location were available. For the 300 international locations, each country’s average retail price was used. In Figure 5, although the building in Italy consumed half the amount of the energy compared with the building in Russia, the economic burdens were four times those in Russia. These economic differences were due to the available inexpensive and abundant natural gas in Russia. Nonetheless, there are many economic issues that vary from country to country, such as value of money and purchasing power. Economic variations make reliance on fixed percentage of savings less effective as we cannot assume that the monetary value of savings has the same economic benefits everywhere.

3.4.2 Environmental and Human Health Impacts

Overall, the environmental performance of each of the 400 buildings varied significantly as well. Sites that depended heavily on coal and other fossil fuels sources had the highest impacts. The results were more complicated when analyzing environmental loads for buildings around the world, as they rely on different energy sources in varying proportions at the same time. Moreover, many environmental and human health aspects varied. In this section the performance of the reference building in 400 locations will be presented in relation to three important issues: climate change, human health and water depletion. Additional results on environmental and human health impacts can be found in Appendix A, Table 6 and Table 8.

Greenhouse Gas Emissions (kg CO_2 eq): This category represents global level impacts, and the results expectedly varied according to the type of primary energy source and the amount of energy needed at each location. Sites that relied on fossil fuels contributed the highest impact for this category. Among fossil fuel types, natural gas achieved the lowest impact and coal contributed the highest impact. Variation between the sites was more significant in the international sample. The means were fairly close between the two samples (512 ton CO_2 eq nationally compared to 471 ton CO_2 eq internationally), but the ranges differed significantly for national compared to the international sites (394 ton CO_2 eq nationally compared to 911 ton CO_2

eq internationally). Overall, sites where a large part of the energy comes from sources other than fossil fuels showed the best results in terms of low environmental impact for climate change. Figure 6 illustrates the extent of variation among the different locations on the left y-axis. Figure 6 also shows the 2012 total CO_2 emissions due to the energy consumption in each region according to the International Energy Statistics from the U.S. Energy Information Administration (EIA) on the right y-axis with a different scale (US EIA 2014). It is noted that the performance of the building does not change given the regional and global context.

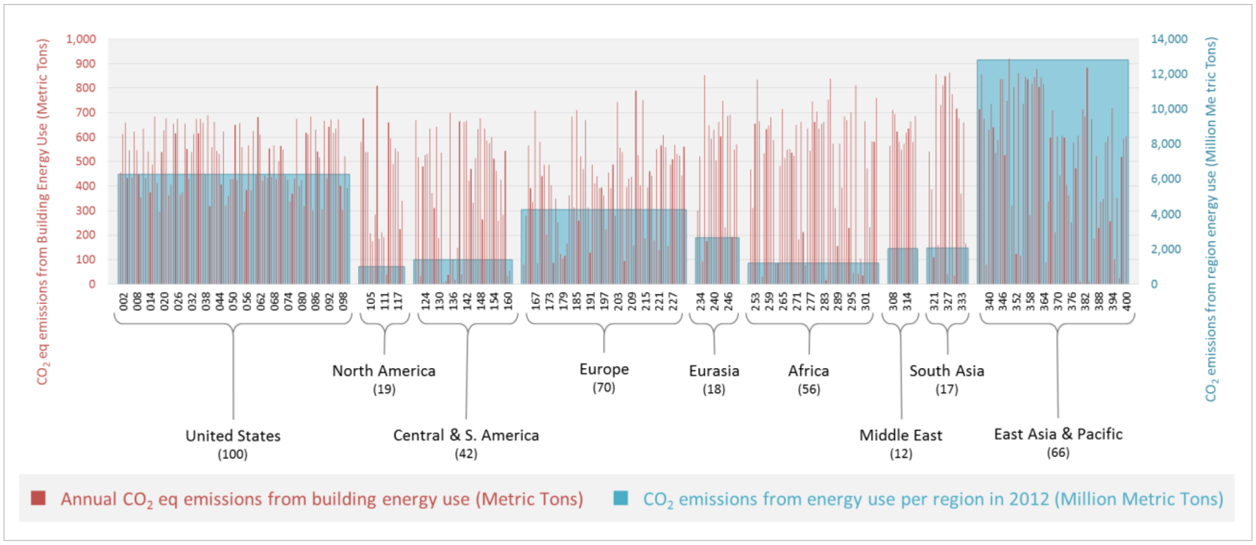


Figure 6. Annual CO_2 emissions, all locations, by region. The red columns represent the potential equivalent CO_2 emissions at each site, referenced on the left in metric tons. The blue shaded areas represent the annual total CO_2 emissions from the energy consumption in each region, referenced on the right in million metric tons.

Human Health (DALY): This category reports the results from the ReCiPe endpoint categories that are related to human health, such as climate change human health, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation and ionizing radiation. Human health impact is expressed in Disability-Adjusted Life Years (DALY).

ReCiPe includes years of life lost and years of life disabled, without age weighting and discounting. Figure 7 illustrates the potential human health damage from each building's energy use and for the 25 lowest/highest locations according to the age-standardized DALYs (per 100,000 population) of each country, information obtained from the World Health Organization (WHO) (World Health Organization 2014). Buildings within the lowest 25, Figure 7 (a), generally demonstrate better performance compared to those in the highest 25, Figure 7 (b). All the buildings shown in Figure 7 (a) and (b) have the same potential to be LEED certified and recognized as green buildings, despite the large variation in the potential human health damage.

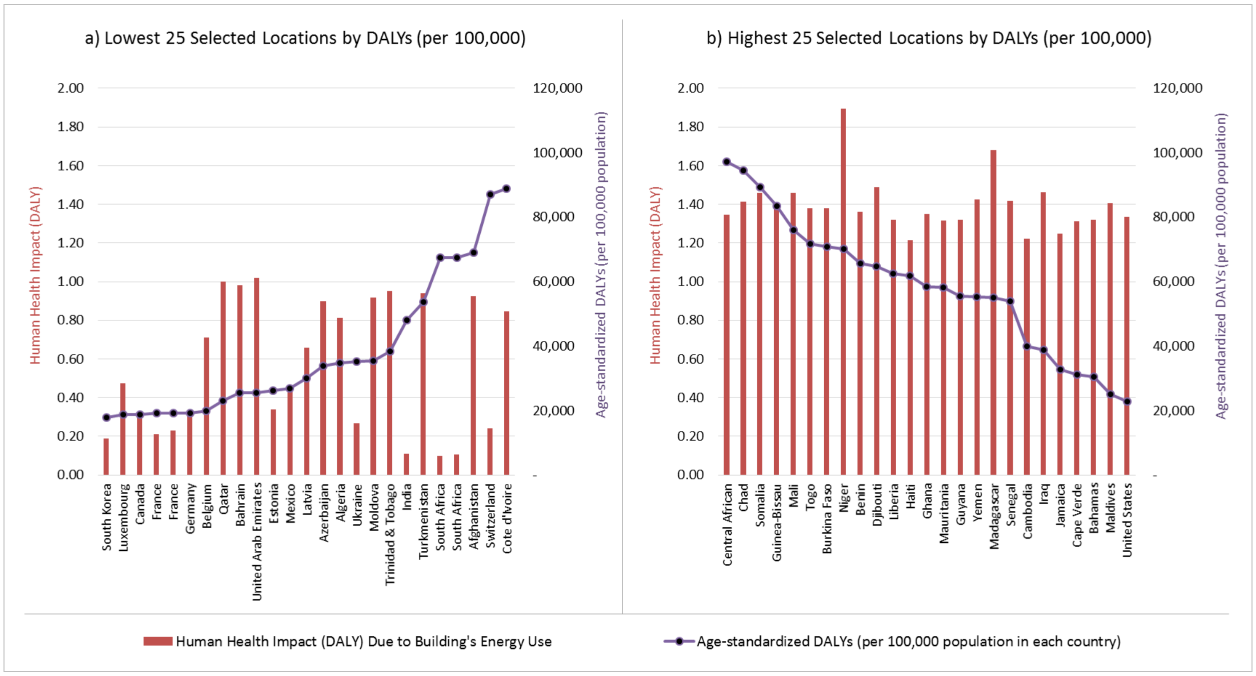


Figure 7. Annual human health damage from building energy in selected locations in disability-adjusted life years (DALY). The red columns represent the potential damage resulting from the building energy use at each location, referenced on the left in DALY using ReCiPe. The purple line with markers represents the age-standardized DALYs (per 100,000 population) for each country from the World Health Organization. Panel (a) shows the lowest 25 locations, while Panel (b) shows the highest 25 locations.

Water Depletion (m^3): This category expresses the water depletion in volume (m^3) resulting from a building's energy consumption, further exploring the water-energy nexus. The results varied significantly according to the type of primary energy source and the amount of energy needed at each location. Nonetheless, it was important to compare water depletion results from energy to the availability of water in each country and the water that would be consumed by the building itself. Figure 8 illustrates the potential water depletion at the 25 lowest and highest locations by water availability per capita of each country in 2005, information obtained from the United Nations' World Water Assessment Program (WWAP) (UNESCO 2014). Figure 8 also shows how much water each building could consume annually using the USGBC Indoor Water Use Reduction Calculator; more clarification can be found in Appendix A. The water usage here does not attain LEED water credits and was used only to show the water/energy connection in a relative context.

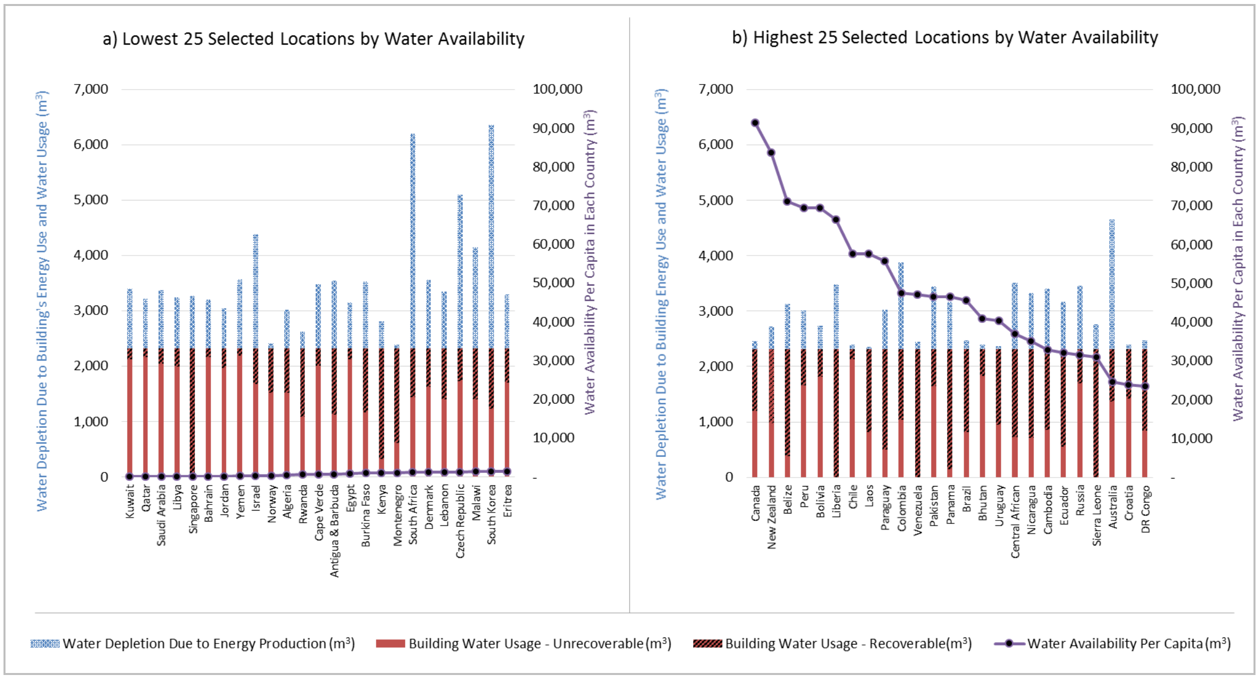


Figure 8. Annual building water depletion, potential use and reuse, and water availability in selected locations. The columns represent the potential water depletion due to building energy use in blue and annual building water use in red. The green portion represents the portion that can potentially be saved through rainwater harvesting and greywater reclamation based on description in text. On the other hand, the purple line with markers represents the water availability per capita (m^3) in each country from United Nations' World Water Assessment Program (WWAP) (UNESCO 2014). Panel (a) shows the lowest 25 locations while Panel (b) shows the highest 25 locations.

Since all of the weather data that was used in the energy models are available, including rainfall information, the amount of water that could be potentially recovered by the building at each location was estimated. The recoverable amount includes rainwater harvesting on catchment areas of the building and greywater reclamation for outdoor usage according to the American Water Works Association (AWWA) (Dziegielewski 2000). As Figure 8 shows, the buildings varied in the amount of water usage and the amount that could be saved or recovered on-site. Water depletion resulting from energy consumption was large in many locations that suffer initially from water vulnerability or even scarcity. In contrast, energy related water depletion was small in locations that have an abundance of water. Here again, all the buildings shown in Figure 8 potentially qualified for LEED certification, despite the large variation in water depletion numbers and the impact on disparate regions.

3.4.3 Limitations and Applicability

For each energy source designated in Figure 4, there are internal subtypes that may have affected the results. For example, coal can be divided into four types: bituminous, lignite, anthracite and peat. Oil can be divided into two types: residual fuel oil and diesel. Hydropower can be divided into three types: run-of-river power plant, pumped storage power plant and reservoir power plant. Renewable sources can be divided into four types: biomass, wind power plant, mix photovoltaic and heat geothermal probe. When the data did not specify the subtype of the source, equal proportions of them were assumed in the original analysis. Another issue is that the efficiency of plants varies from one site to another or from one country to another. As mentioned earlier in the methods section, the IEA efficiency factors were used to adjust efficiency rate and emissions (IEA 2012). However, changes in these proportions and factors represent a limitation for this study as some important differences between energy sources, whether positive or negative, were not addressed. Another factor which may have impacted results is variation among energy sources with respect to other features like flexibility, reliability and energy payback ratio (Gagnon, Bélanger et al. 2002).

3.4.4 Perspectives on LEED

In reviewing all 400 buildings, the LCA results show significant variation in environmental performance among the various buildings. With the international expansion of the LEED rating system, LEED faces even greater challenges regarding regional considerations, especially in the context of diverse types of energy supply and plant efficiencies. Given the range of environmental impacts for the same building in different regions, and given the pressing need to rapidly develop sustainable solutions to mitigate the current global climate crisis, one suggestion is to modify LEED to work towards GHG reduction targets instead of energy reductions without compromising or even improving other environmental impact categories. Another option that future LEED versions may want to consider is that buildings with higher environmental impacts due to energy sources should be required to achieve higher levels of energy savings, efficiency, and/or on-site generation based on the associated impacts instead of fixed percentage of energy savings. Buildings can vary in the EAc2 (Optimize Energy Performance) as these recommendations apply to the prerequisite EAp2 (Minimum Energy Performance).

This chapter investigated the environmental impacts from building energy use in the context of LEED rating systems. The results suggest that considerations of local sources of energy should be used in the development of international GBRS like LEED. This chapter shows that different sites demonstrate considerable variation. It is very difficult and complicated to create a standard that works unilaterally. The variation and magnitude of these differences are depicted in three important categories: Climate Change, Human Health and Water Depletion, as shown in Figures 4, 5, and 6, respectively. Important differences were observed between sites, with the ranges clearly increasing in the international sample and remaining smaller in the national sample. The range in CO_2 emissions was 394 ton CO_2 eq nationally compared to 911 ton CO_2 eq internationally. There are also greater variations in other categories, such as human health and water depletion, with respect to the local/regional needs and challenges.

Since LEED is currently undergoing international expansion, consideration of energy sources for buildings should be included in LEED revisions, with a particular suggestion of targeted goals. This chapter illustrates how GBRS like LEED could work towards targets and the associated rationale. One suggestion is that the LEED EA-p2 prerequisite be modified to reduce energy consumption on a gradual scale according to the LCA results, unlike what is currently in place. Essentially, this modified prerequisite should help address the issue of inconsistencies in the certification by providing reduction percentages that are proportional to the actual environmental impacts associated with the building energy. A higher LEED rating would mean lower impacts compared to other buildings which earned lower certification level.

The LEED rating system, particularly the energy section, could reflect environmental impacts using a clear and precise scientific method for substantial reduction. LCA could be an effective tool and has the potential to be used even more in future development of the LEED, with LEED v4.0 making a considerable step forward. LCA integration into LEED has been an issue in the past; this chapter offers one potential vehicle to effectively integrate LCA into LEED without the resulting methodological or data issues often associated with LEED/LCA integration. Clearly, the focus of this chapter has been on external environmental issues without considering the relationship with ambient air and indoor air quality (IAQ) (Collinge, Landis et al. 2013).

4.0 ON-SITE RENEWABLE ENERGY AND GBRS

The research presented in this chapter addresses research Objective B. Specifically, it answers the questions ‘How can we advance GBRS using LCA to utilize the economic and environmental benefits of renewable energy from a global perspective?’ and ‘How can we understand and model the potential for renewable energy sources in the context of building and systems-level impacts?’

This chapter contains materials related to publications under review by *Environmental Science & Technology* and *Proceedings of the 2014 International Symposium on Sustainable Systems and Technology (ISSST)* (Al-Ghamdi and Bilec 2014b). The materials appear here in accordance with the copyright agreement with American Chemical Society Publications. Supporting Information related to this chapter appears in Appendix B.

4.1 OVERVIEW

In this chapter contains an examination of renewable energy and GBRS at the system level to explore potential benefits and challenges. Adopting a green building rating system that strongly considers use of renewable energy can have important environmental and economic consequences, particularly in developing countries. A case study building was developed using

BIM, and it was put into 25 locations. Then an energy model was built for each site to compute the solar and wind power produced on-site and available within the building footprint and regional climate. A life-cycle approach and cost analysis were then used to analyze the environmental and economic impacts while considering different energy sources (e.g. Coal, Nuclear etc.) and associated prices at each site for the remaining energy needs of the respective buildings. Environmental impacts of renewable energy vary dramatically from one site to another, making the benefits from the environmental point of view irregular; in some cases, the environmental benefits may be very limited despite the significant economic burden of those renewable systems on-site and vice versa. Some economic factors that prevent or reduce the optimum utilization of renewable energy play a role that cannot be undervalued. From a policy viewpoint, this chapter concluded that the requirements of renewable energy generation in existing GBRS need to be developed and changed to be a percentage of what is actually available on-site, instead of a fixed percentage of the energy needed by the building. Likewise, it was determined that buildings with higher environmental impacts due to the type of conventional energy source should be required to achieve higher levels of renewable utilization based on associated impacts.

4.2 INTRODUCTION AND BACKGROUND

The International Energy Agency (IEA) predicts high growth in renewable energy utilization in all sectors, with the highest increases in the building sector. Specifically, by 2035, it is expected that buildings will consume about 34% of final energy consumption from renewable sources (excluding traditional biomass), compared to the 23% predicted in the industrial sector and 15%

in the transportation sector (IEA 2010a). Furthermore, in the next couple of years, renewables are expected to surpass natural gas as the second-largest source of power generation and to approach coal as the leading source by 2035 (IEA 2013). On the other side, in the building design and construction industry, there are many programs and initiatives that incorporate renewable energy use to support sustainable development goals and in line with the previous predictable international trends (GBCA 2010, IBEC 2010, BREEAM 2011, DGNB 2011, Estidama 2012, CBSC 2013, USGBC 2013c, GBI 2014).

Today, GBRS represent an important part in the transformation of building design and construction, including renewable installations. In this chapter, the potential benefits and challenges of using renewable energy in GBRS were studied and explored at the system level and in an international context. Adopting a green building rating system that strongly considers use of renewable energy can offer important environmental and economic considerations, particularly in developing countries.

4.2.1 Renewable Energy and GBRS

Most GBRS include renewable energy; renewable energy requirements are often optional and take the form of credits/points that, when a requirement is met, contribute to a higher level of certification (i.e., silver, gold, platinum). Some GBRS, like BREEAM, use renewable technologies as an option to reduce emissions, allowing the building to earn points when CO_2 emissions are reduced by 10% to 30% (BREEAM 2011). Other systems, such as CASBEE, offer more detail on renewable technologies use, with rules about which types of renewable energy can be used and how much energy needs to be produced on site (IBEC 2010).

In LEED, renewable energy has been a part of the system from the beginning, where LEED has offered credits for renewable on-site generation and contracts with green power providers. LEED's intent was to encourage and recognize increasing levels of self-supply of energy through renewable technologies to reduce the environmental impacts associated with fossil fuel energy use. The requirements and number of points allocated to the renewable energy credit (Energy and Atmosphere, credit 5) have changed from one version to the next, while the amount of green power required (Energy and Atmosphere, credit 7) has to a large extent remained unchanged. However, in previous versions the duration of the green power contract was for two years, whereas in the current version, LEED v4.0, the duration has been extended to five years. Finally, LEED has added a pilot credit with a strategic dimension that supports future use of renewable energy: the pilot credit requires the building structure to be capable of supporting future renewable energy technologies and installation, such as planned photovoltaic technologies for a roof (USGBC 2013c).

Some researchers argue that using a systems-level approach to fully understand environmental impacts, such as LCA, may lead to higher performing buildings (Scheuer, Keoleian et al. 2003, Blengini and Di Carlo 2010). In 2009, LEED implicitly and explicitly integrated LCA by rearranging priorities, where, for instance, energy consumption was given more consideration as opposed to water or indoor environmental quality. This rearrangement in priorities was based on a new weighting scheme, where building impacts are described in terms of 13 impact categories as defined in TRACI (Tool for the Reduction and Assessment of Chemical and other environmental Impacts), developed by the EPA (US Environmental Protection Agency). The weighting scheme compares the impact categories to each other according to BEES (Building for Environmental and Economic Sustainability), a tool developed by NIST (National Institute of Standards and Technology) (Bare, Norris et al. 2002, Gloria, Lippiatt et al. 2007, USGBC 2008). Over the years we can see changes in the requirements and points allocated to each credit due to many factors; for example, the energy-referenced standard was updated, reducing energy consumption at a code level as opposed to an aspirational level. The USGBC strategy for LEED was to exceed the energy code via a prerequisite of fixed percentage of savings from the energy model baseline: 0% in v2.0, 10% in v 2009 and 5% in v4.0 (USGBC 2001, USGBC 2003, USGBC 2005, USGBC 2009, USGBC 2013c). Buildings can achieve points when they go beyond the prerequisite.

4.2.2 Goal and Motivation

This research investigated the environmental and economic impacts of renewable energy (i.e., solar via photovoltaics and wind via turbines) produced on-site for high performance buildings to understand their potential building and systems-level impacts. This research was done to better understand the potential of on-site renewables in the LEED v4.0 rating system on a system-level scale. Specifically, in the most recent LEED, v4.0, a building that produces 1% of its energy requirements receives 1 point; 5%, 2 points; and 10%, 3 points while in the previous version of LEED (version 2009), the on-site renewable points available ranged from 1 to 7. However, at the same time, the IEA is assuming an increase in renewable energy use in buildings. There is an apparent disconnect. The aim is to elucidate the potential of renewable energy in buildings and associated environmental impacts to discern if LEED requirements are at a lower target than a building’s potential.

In the previous chapter, differences were observed in the environmental impacts among sites due to differences in energy sources for the same model building (Al-Ghamdi and Bilec

2015a). The results from the previous chapter suggest that consideration of the energy sources for buildings should be reflected in LEED revisions, with a particular suggestion of targeted goals versus aggregated certifications. This chapter extends the previous life-cycle thinking to examine the relationship between renewable energy potential, GBRS, and life-cycle environmental impacts. It evaluates how much energy the buildings will actually produce and what would happen if GBRS like LEED required that the energy produced on-site be increased in proportion to what already exists for that building (not an outside fixed percentage) and in response to each building's environmental impact. In other words, it evaluates the value of having buildings be credited based on the renewable energy percentage of what is available on-site and can be produced with reasonable economic conditions.

4.3 METHODOLOGY AND PROCEDURE

The reference building that was modeled in the previous chapter using BIM was utilized. Also, the 25 energy models that we developed independently for 25 sites, each of which represents different climatic, economic, natural circumstances, were used. Using Autodesk's Green Building Studio (GBS), each energy model was advanced to compute the renewable energy (solar and wind) produced on-site and available within the building footprint and regional climate. A life-cycle approach and cost analysis were used to analyze the environmental and economic impacts while considering the different energy sources and associated prices at each site.

4.3.1 Reference Building and Energy Models

The case study building is a 43,000 ft^2 (4000 m^2) office building that was designed to be close to the LEED median building of 40,000 ft^2 (3,716 m^2). The building consists of 4 floors to be used for general office space, professional offices, or administrative offices. Operational schedules were set to be the same according to the local time and calendar of each location, taking into account holidays and daylight savings time. All of the building materials that shape the thermal characteristics and other variables in each location (independent from the other sites) comply with the appropriate codes, as will be clarified subsequently. All construction materials meet the minimum R-value requirements ASHRAE 90.1 for each location (ASHRAE, ANSI et al. 2007a). Table 3 illustrates samples of the changes in the thermal properties and construction materials to suit the climatic variations based on the requirements of ASHRAE. Table 3 shows two selected buildings: one from Finland, where the climate is cold and moist, the other from Brazil, where the climate is very hot and humid; it also shows the changes in proportion of northern and southern windows based on the building's location, i.e., if it is in the northern or southern hemisphere.

The 25 reference building models are hypothetical models with ideal operations that meet the aforementioned requirements. GBS, a BIM compatible energy analysis tool that meets the requirements of LEED for calculating a building's baseline performance according to ANSI/ASHRAE/IESNA Standard 90.1 (Appendix G), was utilized(ASHRAE, ANSI et al. 2007a). ASHRAE baseline HVAC system types that matched building type and size were used. Other characteristics and variables were identified as follows: HVAC efficiency and lighting power density were set to meet ASHRAE 90.1 (ASHRAE, ANSI et al. 2007a); equipment power density was set to meet the California 2005 Title 24 Energy Code (California Building Standards Commission 2005); and occupancy density and ventilation were set to meet ASHRAE 62.1 (ASHRAE, ANSI et al. 2007b). Any other characteristics were set by default through GBS to follow the 2003 CBECS (Commercial Buildings Energy Consumption Survey) (US EIA 2003).

Table 3. Detailed description of the thermal properties and construction materials in two selected buildings

Building Components Category	ASHRAE climate zone: 6A (Cold, Humid) **Vantaa, Southern Finland, Finland**		ASHRAE climate zone: 1A (Very Hot, Humid) **Barreiras, Bahia, Brazil**		Total Modeled Area
	Thermal properties	Construction Layers	Thermal properties	Construction Layers	
Roofs	R20 over Roof Deck U-Value: 0.04	1. Blt-Up Roof 3/8in 2. Bldg Paper Felt 3. MinBd 3in R-10.4 4. MinBd 3in R-10.4 5. Wood Sft 3/4in	R15 over Roof Deck U-Value: 0.06	1. Blt-Up Roof 3/8in 2. Bldg Paper Felt 3. MinBd 2in R-7 4. MinBd 2in R-7 5. Wood Sft 3/4in	13,394 ft^2 (1,244 m^2)
Exterior Walls	R13 Wood Frame Wall U-Value: 0.08	1. Wood Shingle 2. Bldg Paper Felt 3. Wood Sft 3/4in 4. MinWool Batt R13 w/(2x4) Frame 16in oc 5. GypBd 5/8in	R13 Wood Frame Wall U-Value: 0.08	1. Wood Shingle 2. Bldg Paper Felt 3. Wood Sft 3/4in 4. MinWool Batt R13 w/(2x4) Frame 16in oc 5. GypBd 5/8in	31,952ft^2 (2,968 m^2)
Interior Walls	Uninsulated Wall U-Value: 0.41	1. GypBd 5/8in 2. Air Space 3. GypBd 5/8in	R0 Metal Frame Wall U-Value: 0.41	1. GypBd 5/8in 2. Air Space 3. GypBd 5/8in	34,903 ft^2 (3,243 m^2)
Interior Floors	R0 Wood Frame Carpeted Floor U-Value: 0.20	1. Wood Sft 3/4in 2. MinWool Batt R0 w/2x4 Frame 16in oc 3. Carpet & Fiber Pad	Interior 4in Slab Floor U-Value: 0.74	1. Conc HW 140lb 4in	29,796 ft^2 (2,769 m^2)
Raised Floors	Uninsulated concrete slab U-Value: 0.03	1. Soil contact for uninsulated slab 2. Soil 8in 3. Conc HW 140lb 8in 4. Carpet & Fiber Pad	U 0.322 Mass Floor U-Value: 0.24	1. Conc HW 140lb 10in 2. Carpet & Fiber Pa	570 ft^2 (53 m^2)
Slabs On Grade	Uninsulated concrete slab U-Value: 0.03	1. Soil contact for uninsulated slab 2. Soil 8in 3. Conc HW 140lb 8in 4. Carpet & Fiber Pad	Uninsulated concrete slab U-Value: 0.03	1. Soil contact for uninsulated slab 2. Soil 8in 3. Conc HW 140lb 8in 4. Carpet & Fiber Pad	12,824 ft^2 (1,191 m^2)
Fixed Windows	2,970 ft^2 North Facing Windows: Double Clear U-SI 3.16, U-IP 0.56, SHGC 0.69, VLT 0.78 (27 windows) U-Value:3.16 W/(m^2-K), SHGC:0.69, Vlt:0.78 9,452 ft^2 Non-North Facing Windows: Double Clear U-SI 3.16, U-IP 0.56, SHGC 0.69, VLT 0.78 (88 windows) U-Value:3.16 W/(m^2-K), SHGC: 0.69, Vlt:0.78		2,736 ft^2 South Facing Windows: Double Clear U-SI 3.16, U-IP 0.56, SHGC 0.69, VLT 0.78 (28 windows) U-Value:3.16 W/(m^2-K), SHGC:0.69, Vlt:0.78 9,686 ft^2 Non-South Facing Windows: Double Clear U-SI 3.16, U-IP 0.56, SHGC 0.69, VLT 0.78 (87 windows) U-Value: 3.16 W/(m^2-K), SHGC: 0.69, Vlt:0.78		12,422 ft^2 (1,154 m^2)
Fixed Skylights	720 ft^2 Non-North Facing Windows: Double Clear U-SI 3.16, U-IP 0.56, SHGC 0.69, VLT 0.78 (80 skylights) U-Value:3.16 W/(m^2-K), SHGC: 0.69, Vlt:0.78		324 ft^2 South Facing Windows: Double Clear U-SI 3.16, U-IP 0.56, SHGC 0.69, VLT 0.78 (36 skylights) U-Value:3.16 W/(m^2-K), SHGC:0.69, Vlt:0.78 396 ft^2 Non-South Facing Windows: Double Clear U-SI 3.16, U-IP 0.56, SHGC 0.69, VLT 0.78 (44 skylights) U-Value:3.16 W/(m^2-K), SHGC:0.69, Vlt:0.78		720 ft^2 (67 m^2)

4.3.2 Renewable Energy Modeling

Today, there are a variety of options and technologies available for on-site renewable energy systems. Those systems are either for electricity generation or thermal systems, with energy coming from solar, wind, geothermal or biomass systems. In this chapter, two types of renewable energy are focused on: solar and wind for electricity generation only. This decision was made due to the limited data available for modeling and to reduce the number of assumptions. Using Autodesk’s Green Building Studio (GBS) and the 25 energy models built previously, the on-site renewable energy sources for each location were modeled and calculated. All data for each site were collected from the nearby weather stations about 1.8 mi (2.9 km) and 3.6 mi (5.8 km) from the building. Figure 9 illustrates 6 selected locations out of the 25 in the study sample. The data comprise: annual solar radiation and annual wind speed. The solar radiation is represented in column charts while the wind is represented in wind roses that show wind speed and gusts direction per time percentage.

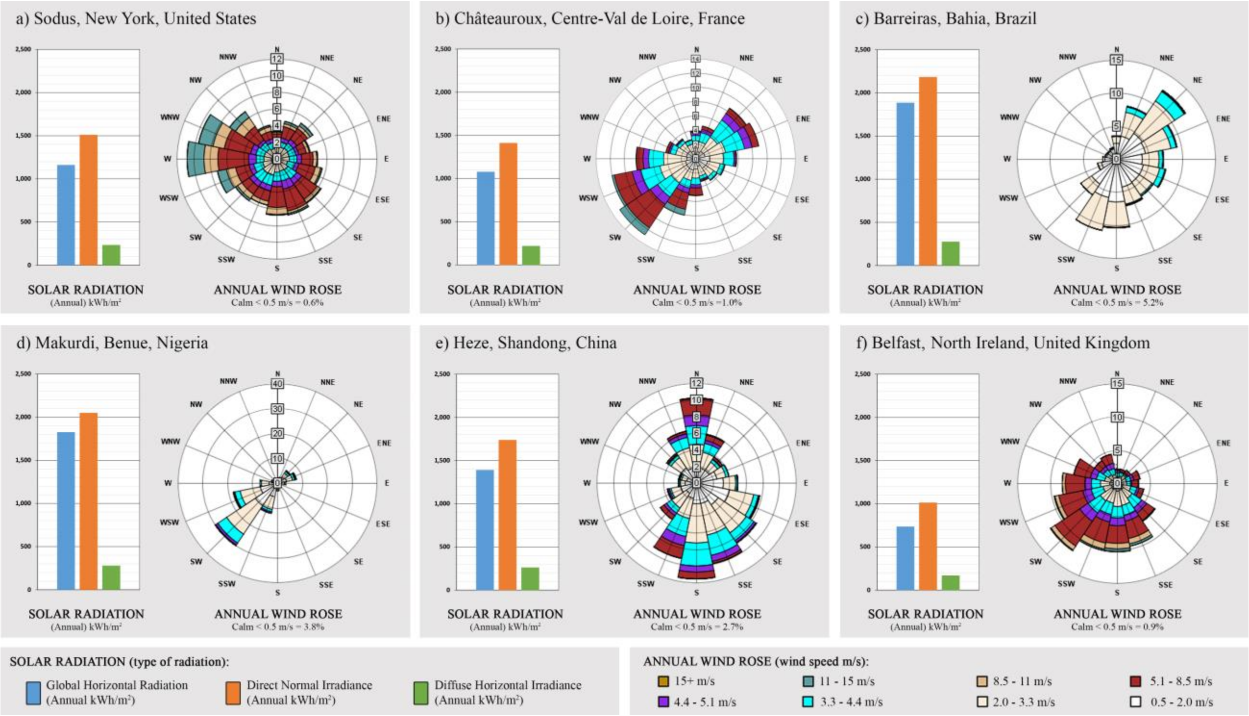


Figure 9. Solar and wind modeling information at 6 selected locations out of the 25 in the study sample. The data were collected from the closest weather station to each building site, the distance ranging between 1.8 mi (2.9 km) and 3.6 mi (5.8 km). The column charts represent the sum of the annual solar radiation in (kWh/m2). The solar radiation data include: Global Horizontal Radiation (GHR), Direct Normal Irradiance (DNI) and Diffuse Horizontal Irradiance (DHI). GHR here is the sum of the DNI and DHI multiplied by the cosine of the angle between the direction of the sun and the zenith (directly overhead). No ground-reflected radiation was considered. The radar chart (wind rose) represents the wind data on site including: wind speed, direction and frequency. The radial scale is the percentage of the time per year, and it is not the same across the different locations.

Solar Power On-Site. Solar energy is the most abundant of all energy resources and has many applications. Currently, the maturity of the various solar technologies available differs, and their adoption and applicability depends on local conditions and government policies (Arvizu, Balaya et al. 2012). Solar energy conversion comprises an enormous group of different technologies designed to satisfy a diversity of energy service needs. Photovoltaic (PV) cells ,or solar cells, are commonly used in building applications compared to other technologies like concentrating solar power (CSP). About 85-90% of the PV market is dominated by wafer-based crystalline silicon (c-Si) cell technologies that include mono- or single-crystalline silicon (sc-Si) and multi-crystalline silicon (mc-Si). Other considerable solar technologies, like thin films, represent 10-15% of the market share. Less than 1% of the market is comprised of technologies like organic solar cells and concentrating PV technologies (IEA 2010b). In this chapter sc-Si with a conversion efficiency of 13.8% was used where the current efficiencies in commercial modules are about 14-20% for sc-Si and 13-15% for mc-Si (IEA 2010b). In the case study buildings, all possible surfaces were utilized, including both roof systems that cover all roofs and façade systems that cover exterior walls and fixed windows through building integrated photovoltaics (BIPV). After the solar modeling of all possible surfaces was done, we then considered only the surfaces that met economic settings; the maximum payback period for each surface was set to not exceed the building life span (50 years). The payback figures did not consider any federal and state energy incentives, tax breaks, loan solutions or system derating factors.

Within the last three decades, substantial cost reductions have been seen in solar technologies, with PV prices falling sharply from about \$22 per watt in 1980 to less than \$1.5 per watt in 2010. Installed prices vary according to country; for example, today's prices in the United States are higher than those in most other major national PV markets (Barbose and Darghouth 2015). These pricing disparities are primarily attributable to differences in soft costs. In this study, a conservative panel cost of \$8.00 per watt (\$102.62 per ft^2) was chosen, based on a study by the Department of Energy's Lawrence Berkeley National Laboratory that examined 37,000 grid-connected PV systems in the United States (Wiser, Galen et al. 2009). The panel cost includes materials and labor to install a complete grid-connected solar electric system.

Wind Power On-Site. In many applications today, wind power is seen as a mature renewable energy source, whether it is on- or offshore, especially in large size applications. Small wind applications that are grid-connected or isolated are also employed for both residential and commercial electricity needs. Many economic and social development benefits can be provided by these different applications. When used in building applications, there are many common challenges. Perhaps the largest is that wind resources are highly site-specific and can be difficult to implement in urban settings. Also, smaller scale wind turbines cost less overall, but are more expensive in terms of cost for each kilowatt of energy produced (Sathaye, Lucon et al. 2012). In this chapter, wind power was employed in a simplified way and mainly for the purpose of comparison. Five on-site wind turbines were assumed (15 ft in diameter, suitable for the office building used in this study), with cut-in and cut-out winds of 6 mph and 45 mph respectively. They were located at the coordinates of the weather data shown in Figure 9.

4.3.3 Life-Cycle Assessment (LCA)

LCA was used to analyze the life-cycle environmental impacts resulting from each building in the 25 different locations. The boundaries of the study (as shown in the Figure 10) focused on two components. First, it examined the life-cycle environmental impacts of each building's electricity consumption, including the full life cycle of power generation from raw materials to power production, but excluding transmission. Second, it looked at the life-cycle environmental impacts of the on-site solar and wind systems, Power transmission was excluded from the study due to high dissimilarity between sites, particularly in developing countries.

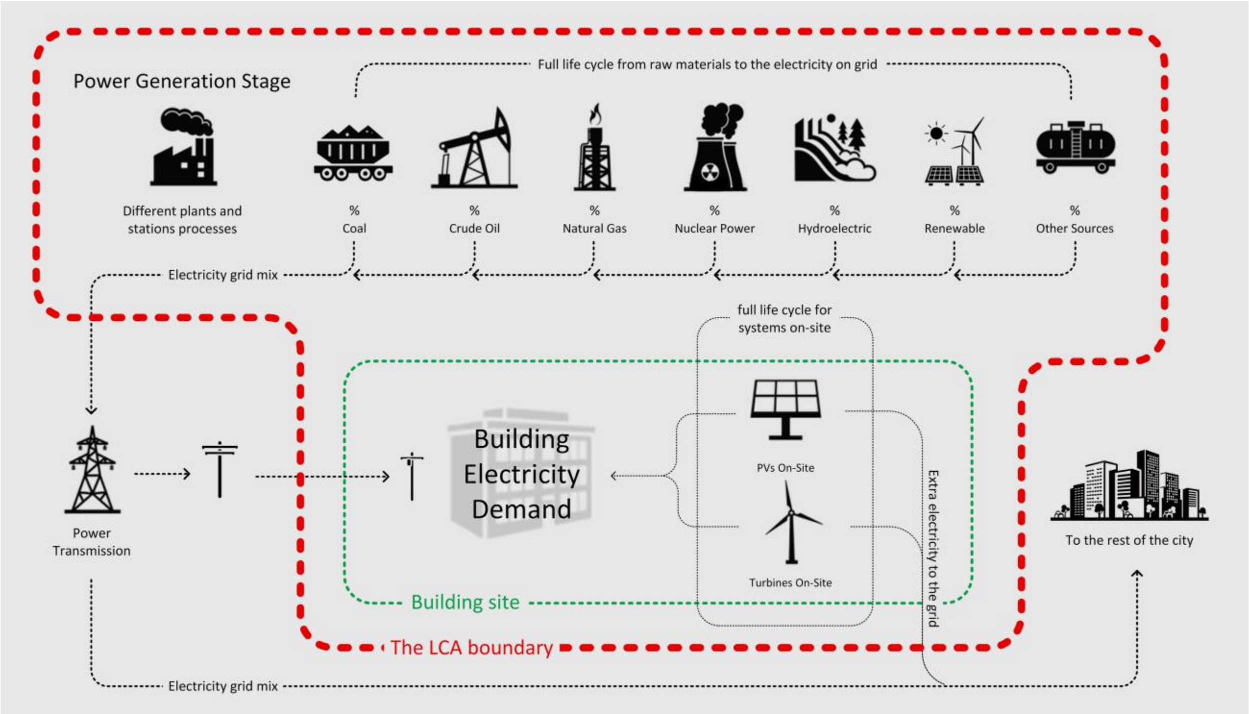


Figure 10. The boundaries of the study within the built environment for each location. Data were collected for the five US sites from the US Environmental Protection Agency, EGRID 2006 Data and 2004 Plant Level Data (US EPA 2012). The data for the other 20 sites were obtained from the 2009 Carbon Monitoring for Action (CARMA) database (CARMA 2009) and International Energy Agency (IEA) database (IEA 2009). The data are presented in detail in Appendix B.

The four steps in LCA were followed (ISO 1997, ISO 2006). The first step, Goal and Scope, involved considering the entire life cycle of the energy used in the building. For this step, the functional unit was the building annual electricity consumption. To complete the second step, Life Cycle Inventory (LCI), data were drawn from US Life Cycle Inventory-based databases (USLCI) (NREL 2010); Ecoinvent (Frischknecht, Jungbluth et al. 2005); then other databases, respectively (ESU Services Ltd. 1996, Franklin Associates Ltd. 1998). For the electric power plant source, data were collected for the US sites from the US Environmental Protection Agency, EGRID 2006 Data and 2004 Plant Level Data (US EPA 2012). For the international sites, data were obtained from the 2009 Carbon Monitoring for Action (CARMA) database (CARMA 2009) and International Energy Agency (IEA) database (IEA 2009). To complete the third step, Life Cycle Impact Assessment (LCIA), the inputs and outputs of each process in the power generation were calculated using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) 2 V3.01. The fourth step, Interpretation, where the significant findings or conclusions are discussed based on the results of the LCIA, is discussed in the subsequent section in detail.

4.4 RESULTS AND DISCUSSION

The central question *"How much energy will the buildings actually produce and what would happen if GBRS like LEED demand that the energy produced on-site be a proportion of what already exists (not a fixed percentage) and in response to each building's environmental impact?"* was first broadly considered. The results from the sample size and models elucidated key variations between sites, variation which was expected due to the variety of energy sources (electricity grid mix), natural resources (i.e. solar radiation and wind speed) and economic conditions (domestic energy prices) present for each. In the photovoltaic analysis, around 20 of the 25 buildings were physically capable (i.e., based on building size, geometry and solar potential) of producing 20% to 40% of the buildings' electricity requirements, leading to economic savings of $20,000 to $100,000 (see Figure 11) and greenhouse gas emission reductions of 635,000 to 1,347,000 kg CO_2 equiv per building per year (see Figure 12). In the wind analysis, 2 buildings were able to produce 5% and 9% of their electric requirements with economic savings ranging from $6,000 to $11,000, respectively. Eight other buildings were able to produce only 1% or less of theirelectric requirements using wind power. The overall wind contribution in the mitigation of equivalent CO_2 emissions ranged from 8,500 to 86,000 kg. The next sections summarize the main features garnered from the results regarding energy and economic performance and overall environmental impacts (see Figure 11 and Figure 12).

4.4.1 Energy and Economic Performance

While the size and function of the building were identical in all of the locations, the consumption of electricity varied based on the different climatic conditions in each context (Al-Ghamdi and Bilec 2015a). These variations existed even though the building interacted with the climate by increasing thermal insulation levels according to the energy code (ASHRAE 90.1), as described in Table 3. The electricity consumption, as shown in Figure 11, ranged from 500 to 800 MWh/year while the economic burden of this consumption varied significantly from $11,500 to $207,000 per year depending on the local economic circumstances at each location. The total system payback period for the 25 locations ranged from 19 to 48 years based on the potential renewable energy availability on site and the prices of domestic electricity.

The photovoltaic results also varied from one location to another, both in the amount of electricity produced and in the area of roofs and walls covered by photovoltaic panels. Utility rates often vary significantly by time of day and by season and are typically highest during afternoon hours in the summer, when PV production is highest. However, because the calculations did not take into account daily or seasonably higher rates, but instead used a flat rate, the calculated payback period is conservative (longer) than the actual payback period is likely to be. Applied electric costs (utility rates) were based on average domestic prices, with the assumption that energy prices would increase by 2% per year.

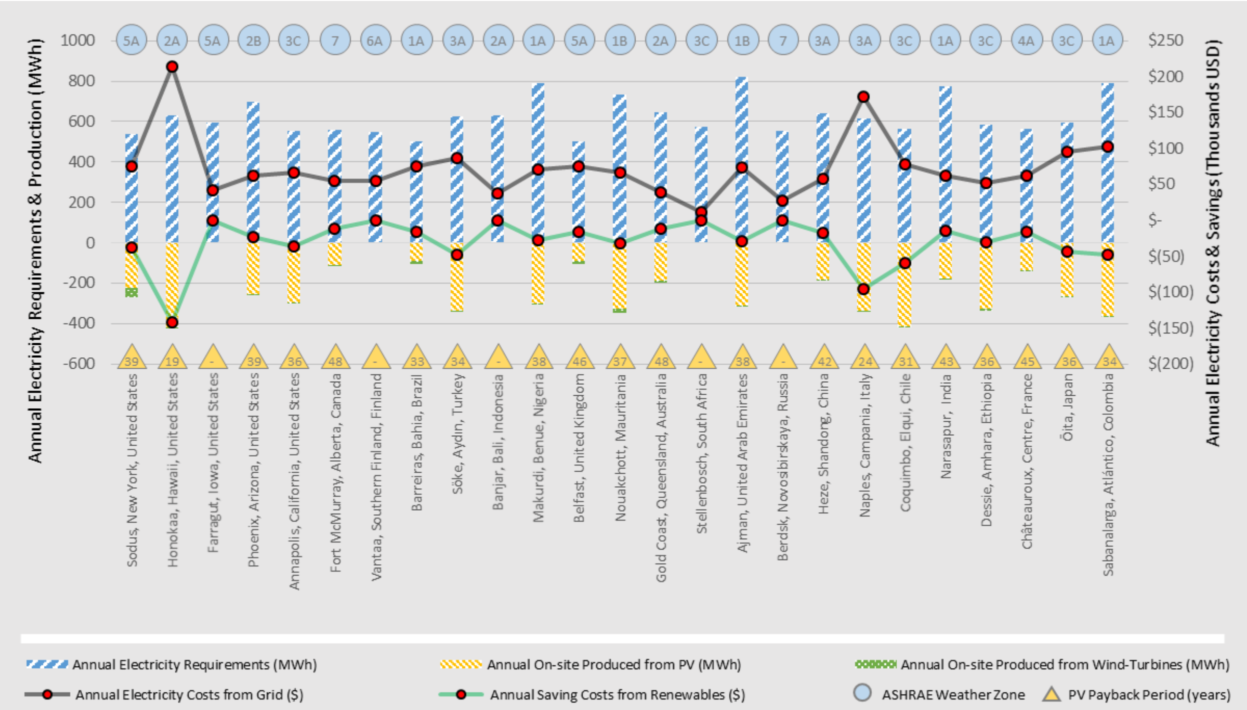


Figure 11. Annual electricity requirements, renewable production, payback, and cost for the 25 locations included in the study. The columns represent the annual electricity requirements at each site and the renewable potential production on site, referenced on the left in (MWh). The lines with red markers represent the annual electricity cost and the annual savings at each site, referenced on the right in thousands of US dollars. The blue circles indicate the ASHRAE climate zone. The yellow triangles indicate the PV system payback period in years and is associated with the electricity production from PV (yellow columns).

The local economic circumstances play a major role in the development of renewable energy. In the results for the 25 locations, as shown in Figure 11, domestic energy prices dominated the results of the renewable energy sources on site. The locations can be classified into 3 groups according to economic performance. First, locations like Hawaii and Italy show good performance compared to the others, due to the moderate availability of renewable energy sources and high prices of conventional power from the grid. In Hawaii and Italy the building can produce about 45% and 55% of its electricity needs, respectively, from solar only; the payback period for both locations was 24 years. The buildings in these locations also can produce about 5% and 1% of its required electricity, respectively, from wind power. The annual savings were about $105,000 in Hawaii and $96,000 in Italy. Second, some locations, like Chile, showed an excellent performance due to the high availability of renewable energy sources and moderate energy local prices. The building in Chile can produce about 74% of its required electricity using solar power and 1% from wind power. However, despite the high percentage of production on site in Chile, the payback period was still around 31 years and annual savings only around $59,000. Third, locations like Iowa, Finland, South Africa and Russia show poor performance as those locations are unlikely to take advantage of renewable energy due to the cheap prices of conventional power from the grid, regardless of the availability of renewable energy on-site. The location in Iowa, USA, for example, was not able to produce electricity from renewable energy sources despite the higher levels of solar radiation and wind speed due to cheaper electricity prices compared to the locations with similar access to renewable energy sources like Alberta, Canada.

4.4.2 Environmental Impacts

Environmental impacts depend on the primary sources of the energy of a particular place. In buildings, the use phase and associated energy use represent the greatest environmental impacts (Aktas and Bilec 2012), approximately seventy to ninety percent (Ortiz, Castells et al. 2009b). The environmental impacts of energy use in buildings can be significantly reduced by the use of renewable energy sources (Citherlet 2007). The environmental impacts of the 25 buildings modeled become more complicated to understand as the environmental loads for buildings around the world are analyzed, as they rely on different energy sources. As shown in Figure 12, essential discrepancies were observed in the results among sites, with differences clearly increasing with more diversified energy sources. Range of variation in emissions was from 2,244 and 2,465 kg CO_2 equiv in Brazil and Japan, respectively, which have dominant energy sources of hydro and nuclear, respectively, to 851,427 and 759,588 kg CO_2 equiv in India and China, respectively, which both have coal as the dominant energy source.

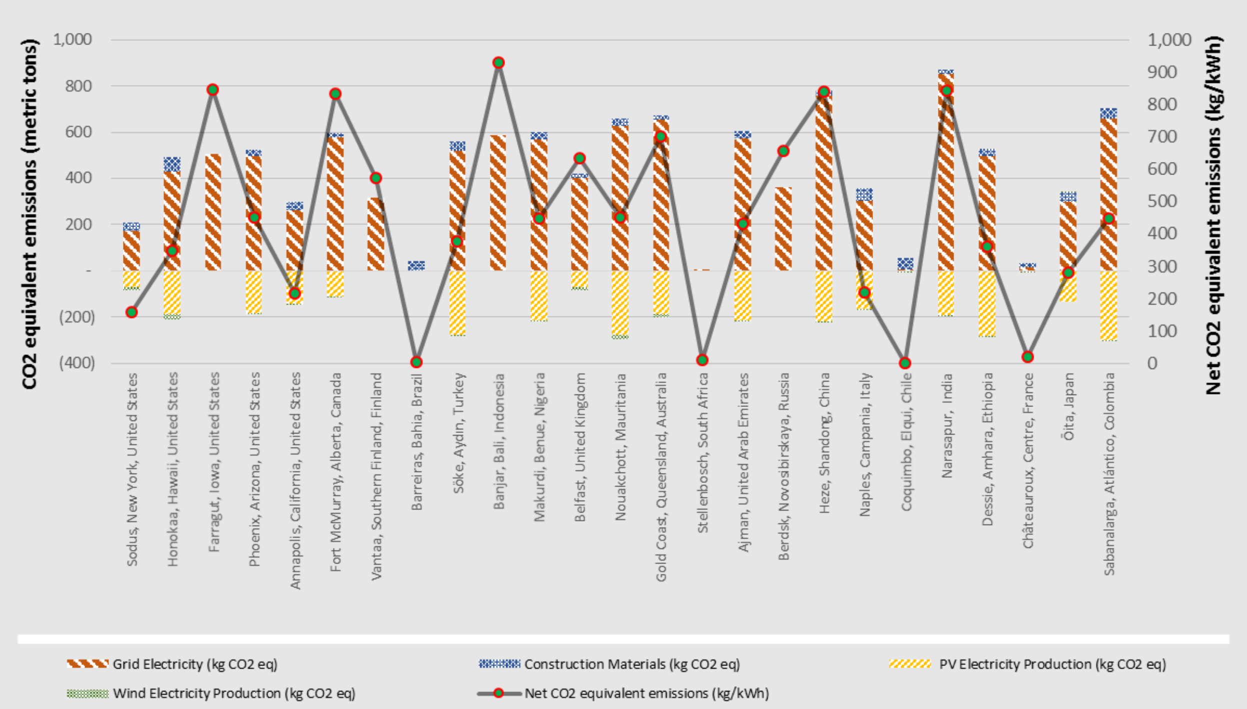


Figure 12. Annual Life Cycle CO_2 equivalent emissions in the 25 locations included in the study – use phase. The stacked columns represent the potential CO_2 equivalent emissions at each site, referenced on the left in metric tons. The blue portion denotes the impact from the systems on site comprising the entire system cradle-to-grave life cycle. The orange portion denotes the impact from the annual grid electricity consumption. On the negative side, the yellow portion denotes how the impacts can be mitigated using a PV system while purple shows how the impact can be mitigated using wind turbines. The lines with green markers represent the annual net CO_2 equivalent emissions, referenced on the right in kg per kWh.

The mitigated environmental impacts were limited despite the significant economic burden of renewable systems in locations such as Brazil, Chile and France. The limitation here was due to the prior utilization in these sites of electricity that was generated from non-fossil fuel resources, hydroelectric power in the case of Brazil and Chile, nuclear power in the case of France. For example, the building in Chile was capable of producing about 74% of its electricity requirements, yet its environmental footprint was minor compared to others because its initial energy source was hydroelectric. On the other hand, the buildings in China and India, have smaller savings percentages in electricity (23% and 29%); however, the carbon emissions mitigation amount was around 50 times greater compared to that in Chile, as China and India are more dependent on fossil fuels. The highest environmental benefits (minimal emissions) were in Ethiopia, Mauritania and Colombia. The results for these locations present an optimistic outlook of what renewable energy on site can do, in developing countries particularly.

4.4.3 Outlook for GBRS and Renewable Energy

GBRS like LEED play a significant role in increasing the efficiency of buildings and therefore in reducing their economic and environmental burdens. GBRS employ renewable energy on site to increase self-supply and reduce the environmental and economic harms associated with fossil fuel energy (BREEAM 2011, USGBC 2013c). GBRS streamline the use of renewable energy in buildings, often by requiring a fixed percentage of renewable on-site utilization, and award points/credits incrementally based on this percentage. However, according to the results shown in this paper, some of the buildings can self-produce more energy than others with the same economic circumstances (with the payback period of any given surface not exceeding the building life span of 50 years), and some other buildings cannot produce any energy on site at all. For example, the buildings in Hawaii, California, Turkey, Chile, Italy and Ethiopia can produce more than 50% of their electricity needs from renewables on site. However, the buildings in Iowa, Finland, Indonesia, South Africa and Russia were not able to produce any energy on site at all either due to the lack of renewable energy sources or/and economic constraints. The economic factors that prevent or reduce the optimum utilization of renewable energy play a role that cannot be undervalued. Environmental impacts of renewable energy vary dramatically from one site to another, making the benefits from the environmental point of view irregular; in some cases, as mentioned in this paper, the environmental benefits may be very limited despite the significant economic burden of those renewable systems on site and vice versa. From a policy viewpoint, and as the results in this chapter show, the existing requirement of a fixed percentage of renewable energy use in today's GBRS has deficiencies. Different renewable energy technologies have considerable variations in their economic and the environment impacts. Moreover, the wind power (turbines) in this study shows very limited benefits for the case study building compared to solar (PVs). The variations here highlighted the need for today's GBRS to be more sophisticated in dealing with renewable energy by implementing more detailed requirements that can maximize the benefits of various renewable energy technologies.

A reflection how consider energy sources and renewable energy availability on site is particularly crucial at this point in time since GBRS are currently evolving and undergoing international expansion, with a particular focus on the idea of targeted goals versus nominal percentages. The recommendation for LEED and other GBRS is to require buildings with higher environmental impacts to achieve higher levels of energy renewable performance based on associated impacts instead of on the current fixed percentage of improvement. For example, renewable energy generation may be a percentage of what is available on site instead of a fixed percentage of the energy needed by the building. The results of this study reveal that location-specific results, when paired with life-cycle assessment, can be an effective means to achieve a better understanding and reduction of the adverse environmental impacts resulting from energy consumption.

5.0 WHOLE-BUILDING LCAS AND GBRS

The research presented in this chapter addresses research Objective C. Specifically, it answers the questions ‘What are the means available now to designers to assess whole building LCA?’ and ‘What are the advantages and disadvantages of each tool and the possibility of employing each through GBRS?

This chapter contains materials related to a publication in *Proceedings of the 2015 International Symposium on Sustainable Systems and Technology (ISSST)* (Al-Ghamdi and Bilec 2015b) and *Proceedings of the 2015 International Conference on Sustainable Design, Engineering and Construction (ISSST)* (Collinge, Thiel et al. 2015). The materials appearing here with copyright agreement with Elsevier Ltd. Supporting Information related to this chapter can be found in Appendix C.

5.1 OVERVIEW

There is a growing interest in integrating LCA into building design decision-making due to LCA’s comprehensive, systemic approach to environmental evaluation. Many GBRS use LCA to various degrees. In this chapter a comparative study has been performed to evaluate the LCA software tools available to building designers. A whole-building LCA was performed for a large building using three software LCA tools: (Athena Impact Estimator for Buildings, Kieran Timberlake’s Tally and SimaPro). The software tools vary in key aspects such as intended users (e.g., LCA experts or novices), design stage where they can be used, and time. The evaluated LCA tools varied significantly in the possibility of their use in early design and decision-making. Some of the applications rely on a bill of materials that changes constantly in design alterations. However, others showed a greater advantage, where it can be integrated from the beginning of the design process. The comparative LCA results indicated that the impact of LCA software is dependent on the impact category and the precision in the process of materials quantities take-off. The case study was influenced by the building type and its intense operational energy requirements. Conventional energy efficiency measures like increasing the lighting efficiency exceeded by far what can be done to mitigate the embedded impact of construction materials. Thus, advancing the requirements of the LCA baseline building and addressing the operational phase in a more comprehensive framework are discussed. Finally, this chapter examined the traditional building’s systems that are usually involved in LCA and the possibility of adding other systems such as plumbing, HVAC and electrical systems using BIM.

5.2 INTRODUCTION AND BACKGROUND

Buildings provide countless benefits to society; nonetheless, they can have substantial environmental and human health impacts. The building sector is the largest energy consumer in the US and worldwide (US EIA 2012). Civil works and building construction consume 60% of the global raw materials extracted from the lithosphere. In Europe, the mineral extractions per capita intended for buildings accumulate up to 4.8 tons per inhabitant per year, which is 64 times the average weight of a person, highlighting the need to work towards dematerialization in building (Zabalza Bribián, Valero Capilla et al. 2011).

While the architecture, engineering, and construction (AEC) industry is often acknowledged as a low-technology and an inefficient industry (Gallaher, O’Connor et al. 2004), this industry is undergoing profound and rapid transformation. Illustration of this transformation can be seen in the trend towards green buildings and sustainable development. For example, 94% of AEC firms report some level of engagement in activities associated with green building. Those activities either aim to certify the building under any known international green building rating system or to be constructed to meet the certification requirements under a similar system. A substantial 28% of the AEC professionals report high levels of green activity engagement, with more than 60% of their work being green or sustainability driven. These high levels of green building activity are expected to grow (McGraw-Hill Construction 2013).

There is growing interest in integrating LCA into building design decision-making, due to LCA’s comprehensive, systemic approach to environmental evaluation. There are many challenges that practitioners may encounter in the use of LCA, especially in the context of GBRS. LCA may have beneficial contributions on several levels such as at the pre-design, schematic design, and design development stages of the design process. LCA can support architects and engineers in answering questions that arise throughout the design and construction and assist in their decisions by providing scientific and methodical justifications. In this chapter, a comparative study has been performed to evaluate the tools available to designers at different design stages and their use as a means to meet various GBRS requirements.

5.2.1 LCA and Green Building Rating Systems

Since the early nineties, LCA has been used as an assessment tool in a building's construction sector and has grown and expanded (Fava 2006). Today, there are many GBRS that use LCA to assess environmental goals. Some rating systems and/or codes that have LCA provisions include: LEED by the U.S. Green Building Council (USGBC 2013c); BREEAM by the U.K. Building Research Establishment (BREEAM 2014); IgCC by the International Code Council (ICC 2012); Green Globes by Canada ECD Energy and Environment (GBI 2014); and CALGreen by the California Building Standards Commission (CBSC 2013). Requirements vary from one to another and are likely to evolve in future versions.

For example, in LEED, the most prevalent and commonly used rating system, LCA was integrated as a pilot credit in 2009 for building assemblies and materials to encourage the use of environmentally preferable building materials and assemblies. LCA was not only used explicitly through the LCA credit but implicitly incorporated into the current version of LEED, with likely expansion in the next versions, given the prominence of Environmental Product Declarations (USGBC 2009, USGBC 2013c).

In the LCA credit in LEED, the design team has the option to perform a whole-building LCA and receive 3 points. The LCA should cover the project's structure and enclosure and exclude energy consumption during the period of the building's operation. The LCA results should demonstrate a minimum 10% reduction, compared with a baseline building, in at least two self-selected life-cycle impact categories (i.e. acidification of land and water sources; eutrophication, in kg nitrogen or kg phosphate; etc.), plus reduction in global warming potential as a mandatory category (USGBC 2013c). Comparison with a baseline building model, such as energy models, is a prevailing practice in many GBRS and in some codes and standards. In

LEED, a building can achieve points in the water and energy categories by demonstrating reduction beyond a baseline building that was created based on a specified reference standard. For example, in the energy category, the baseline building must meet the ASHRAE 90.1, which is a longstanding standard that has undergone more than forty years of technical and scientific development.

5.2.2 Today's Building Design and Construction Industry

Synergies and interconnectedness in the building design process are critical to green building design. Today's practitioners work in a more collaborative work environment. Whole building design relies on two components: an integrated design approach and an integrated team process. Today's technologies support practitioners, making it easier to realize a green building through an integrated approach. BIM is seen as one such tool/technology that can aid the building stakeholder community in accomplishing design objectives. BIM is the system of production and management of a building's data during its life cycle; BIM combines 3-D modeling with time and cost (Lee, Sacks et al. 2006). Although BIM has been available since the late 1980s, it did not evolve as a valuable tool for aiding in meeting sustainability objectives in the building sector until the green building revolution in 1990s. BIM extends to cover the different phases of the building design processes, where a massive amount of data is generated. BIM differs radically from the principle of Computer-Aided Design (CAD) in that BIM models, unlike CAD models, manage not just graphics, but also information. While the use of BIM has encountered many legal and technical obstacles, BIM demonstrates benefits in the field of professional practice in areas such as sustainable design, construction, facilities management and estimating (Becerik-Gerber and Kensek 2010).

5.3 METHOD

This chapter describes a whole-building LCA performed for a large hospital in Pittsburgh, Pennsylvania using three different process LCA tools. Those tools are: Athena Impact Estimator for Buildings, Kieran Timberlake's Tally and SimaPro. The tools vary systematically in the way they were built, user skill required and the design stage where they can be used. The LCAs developed in this work represent complete architectural, structural, and finish systems, and they were used to compare the relative contributions of building systems to different environmental impacts. The analyses accounts for the full cradle-to-grave life cycle, including material manufacturing, maintenance and replacement, and eventual end-of-life. It includes the materials and energy used across all life-cycle stages of the hospital's building.

5.3.1 Case Study Building

The case study building was Magee-Womens Hospital (MWH). MWH is a University of Pittsburgh Medical Center specialty hospital, catering primarily to women. Magee is one of the top women's hospitals in the United States and is ranked 9th for gynecology, with more than 10,000 babies delivery each year (US News & World Report 2015). It was chosen as the case study for this chapter because it is a very complex building and therefore illustrates the worst-case scenario. The hospital is located in the Oakland neighborhood of Pittsburgh, Pennsylvania and has established green initiatives in recognition of Practice Green health and the U.S. Environmental Protection Agency's Office of Children's Health Protection recommendations. It is currently equipped with 360 beds, an emergency room, and ambulatory facilities. A total of

2,500 employees and 1,500 medical staff serve in this facility (UPMC 2015). Figure 13 illustrates multiple views of the hospital building after modeling using BIM.

Figure 13. Multiple views of the case study building MWH. The views show the actual building and after it was modeled using BIM. The total area of the building is about 957,927 ft^2 (291,976 m^2), and it consists of three wings in five floors above ground and one floor underground.

The BIM model was developed using Autodesk Revit for the entire hospital building based on the CAD drawings that were obtained from hospital administration. The building consists of three wings in five floors above ground and one floor underground, with a total occupancy of 8,000 users and total area of 957,927 ft^2 (291,976 m^2). To put the case study building in perspective, average US floor space of inpatient health care buildings is around 238,000 ft^2, representing 3% of the total floor space in all commercial buildings and 6% of the total primary energy consumption by commercial building (US EIA 2003). Also, average US energy expenditures per square foot for the same building type are \$2.76 whereas MWH spends \$3.76 per square foot. For the characteristics of the building, MWH has 183,754 ft^2 (56,008 m^2) in roof space. The exterior wall area is 264,150 ft^2 (80,512 m^2). Fixed windows cover around 20% of the exterior walls, with an area of 55,269 ft^2 (16,846 m^2) and about 36% of them facing north. Operable windows cover around 0.6% of the exterior walls, with an area of 15,988 ft^2 (4,873 m^2) and about 18% of them facing north. Skylights cover about 1,524 ft^2 (465 m^2) of the roofs. Exterior doors cover around 0.006% of the exterior walls, with 1,723 ft^2 (525 m^2). The underground wall area is 52,023 ft^2 (15,857 m^2), with 201,462 ft^2 (61,406 m^2) of underground slabs.

All operational data for MWH was obtained through hospital management. The data represent the building's energy consumption in a whole year, covering various functions inside and outside the building, such as interior/exterior lighting, HVAC, treatment/pumping and water heating. In this chapter, Autodesk Green Building Studio (GBS) Version 2014.2.31.4804 (DOE-2.2-44e4) was used for the analysis and simulation of energy. GBS meets ANSI/ASHRAE/IESNA Standard 90.1-2007, Appendix G, which meets LEED requirements for calculating a building’s baseline performance (ASHRAE, ANSI et al. 2007a). The MWH building uses natural gas for HVAC and water heating purposes and uses electricity for the rest of its energy requirements. On an annual basis, MWH consumes 152,800 Mcf (thousand cubic feet) of natural gas at a cost of \$1,036,258 and 32,915 MWh of electricity at a cost of \$2,568,375. To provide more context for the case study building (MHW) , it is located in the Northeast (Middle Atlantic) of the United States, which is classified as a (A5) Cool-Humid weather zone: 5,400 < HDD-65°F ≤ 7,200 and less than 2,000 CDD-50°F. On average, hospitals in zone A5 consume 272.54 kBtu/ft^2/year compared to 253.8 kBtu/ft^2/year nationwide (US Energy Information Administration (EIA) 2003). That is very similar to a large extent with the case study building, where MWH utility bills show that the actual consumption was around 280 kBtu/ft^2/year.

5.3.2 Building LCA software Tools

Three LCAs were completed of MWH using the three different LCA tools: ATHENA's Impact Estimator, Kieran Timberlake's Tally and PRé's SimaPro. Table 4 compares the key elements of the tools. The tools vary with respect to LCA databases used; for example, Athena primarily draws from U.S. LCI; Tally from GaBi; and SimaPro from multiple databases, including Ecoinvent.

Table 4. Comparison of the general characteristics of the three tools used in study

Comparison Category	**Athena** Impact Estimator for Buildings	Kieran Timberlake's **Tally**	PRé **SimaPro**
Level of analysis or type	Whole building analysis	Whole building analysis	Product analysis tool
Building Type	Industrial, Institutional, Commercial, Residential for both New Construction and Major Renovation	Any type, including both New Construction and Major Renovation	Complex products with complex life cycles
LCA Stages	Material Extraction and Manufacturing, Related Transport, On-site Construction (energy use + related emissions), Operation (energy only), Maintenance and Replacement, Demolition and Transport to Landfill.	Cradle-to-Grave Manufacturing; Maintenance and Replacement; End of Life. Operation phase (energy only)	Cradle-to-Grave Manufacturing; Maintenance and Replacement; End of Life. Operation phase (energy only)
LCI Database	ATHENA Database (cradle-to-grave), US LCI Database	GaBi LCI databases	US LCI Database; Ecoinvent
Data Location	Canada and US Region	US Only	US and World
LCIA Method	EPA TRACI	Multiple (EPA TRACI used)	Multiple (EPA TRACI used)
Impact Categories	▪ Acidification ▪ Potential Global Warming ▪ Potential Human Health ▪ Respiratory Effects Potential ▪ Ozone Depletion ▪ Smog Potential ▪ Aquatic Eutrophication Potential ▪ Total Fossil Energy	▪ Acidification Potential ▪ Eutrophication Potential ▪ Global Warming Potential ▪ Ozone Depletion Potential ▪ Smog Formation Potential ▪ Primary Energy Demand	▪ Climate change ▪ Carcinogens ▪ Respiratory organics ▪ Respiratory inorganics ▪ Radiation ▪ Ozone layer ▪ Ecotoxicity ▪ Acidification / eutrophication ▪ Land Use
Target Users	Architects, Engineers, Designers, Environmental Consultants	Architects, Engineers	LCA Practitioners
Skill Level	Moderate	Advanced level in BIM	Advanced

All three follow the four steps in a standard LCA as established by the International Organization for Standardization (ISO) in ISO 14040 and 14044 (ISO 1997, ISO 2006). The following section explains in detail the procedures performed in each step.

5.3.3 Life-Cycle Assessment

The four steps in and LCA include: Goal and Scope; Life-Cycle Inventory (LCI); Life-Cycle Impact Assessment (LCIA); and Interpretation. In Athena and Tally, there are few options regarding those four steps, but in the case of SimaPro, there are many options.

Goal and Scope. The functional unit of the study is the usable floor space of MWH. The reference flow is the amount of material required to produce the hospital building and the energy required for the operational phase over the full life of the building. The modeled life of the building was 60 years. The analysis accounts for the full cradle-to-grave life cycle of the three different LCA tools, including material manufacturing, maintenance and replacement, and eventual end-of-life (disposal, incineration, and/or recycling), which covers the energy used across all life cycle stages. Architectural materials and assemblies include primary materials and all additional materials required for the product's manufacturing and use (including hardware, sealants, adhesives, coatings, and finishing, etc.) up to a 1% cut-off factor by mass, with the exception of known chemicals that have high environmental impacts at low levels. In these cases, a 1% cut-off was implemented by impact.

Life-Cycle Inventory (LCI). The analysis requires generating material quantities prior to the development of robust LC inventories. Each tool provides a different approach to estimating the material quantities. For Tally, there is a direct link with BIM and the material quantities are completed automatically. The same material quantities from BIM/Tally were then used in Athena and SimaPro.

In Athena and SimaPro the type of materials were set to match what was chosen in Tally to reflect the same building design of MWH and ensure as much consistency as possible. For example, the same characterization of the brick in the exterior wall was matched in the three different tools: Tally, Athena and SimaPro. Tally here plays an important role in helping to customize the bill of materials before inputting data into Athena and SimaPro. The selection of LCI unit processes were limited in Athena and Tally, where the user can only select the type of the material with no options to change the data source or details. However, in SimaPro the LCI unit processes could be selected manually to provide more detail on the source of the data. In this study, the LCI unit processes in Tally was from GaBi databases, while in Athena data wasfrom Athena's Database and US Life Cycle Inventory-based databases (NREL 2010). In SimaPro, the LCI unit processes were selected mainly from US Life Cycle Inventory-based databases (USLCI). However, when unit process were not available in USLCI, other databases like ecoinvent were used (Frischknecht, Jungbluth et al. 2005).

For the occupancy phase of the MWH building (operational side of the analysis), the selection of the LCI varied in the following ways: in Athena and Tally the location (Pittsburgh, Pennsylvania, USA) of the case study building is already a part of the applications where the energy mixes considered. However, in SimaPro, the entire life-cycle of energy was modeled, where the LCI unit processes were selected mainly from US Life Cycle Inventory-based databases (USLCI) (NREL 2010). The electric power plant source data was collected for MWH from the US Environmental Protection Agency, EGRID 2006 Data and 2004 Plant Level Data (US EPA 2012). The electricity in that part of Pennsylvania comes from the following sources: Coal 69.9%, natural gas 3.5%, Oil 0.4%, Nuclear 23.6%, Hydro 0.8% and Non-Hydro Renewables 1.4%.

Life-Cycle Impact Assessment (LCIA). The environmental impacts of the inputs and outputs of each process were calculated using the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) in the three different tools. As shown in

Table 4, TRACI is the only LCIA methodology available in Athena but there are more methodologies available in Tally and SimaPro, such as IMPACT 2002+, BEES, ReCiPe etc. TRACI is a midpoint method tool that was developed by the US Environmental Protection Agency to facilitate the characterization of environmental stressors which have the potential to contribute to impacts (Bare 2002, Sharaai, Mahmood et al. 2010). The impact categories under focus in this study are three impact categories included in LEED (USGBC 2013c). Global warming potential was a mandatory category and two other impact categories were selected: acidification of land and water sources and eutrophication.

Interpretation. In this step ISO 14040 requires a clarification of the limitations and evaluation of the assessment considering completeness, sensitivity and consistency checks (ISO 2006). The three different tools vary in how they display the LCIA results. This variation causes users to interpret the results in different ways and so perhaps come to differing conclusions and decisions. The following section will cover this step (interpretation) in more detail.

5.4 RESULTS AND DISCUSSION

The results and discussion have been divided into two main parts. The first part qualitatively documents and presents a comparison of the three tools on five core issues: integration with design capability, transparency in the analysis process, building systems, included geographical area covered, and user LCA experience required. The second part presents a detailed comparison of whole-building LCA results of the case study building (MWH) for the three different tools, examining embedded and operational environmental impact.

5.4.1 Perceived advantages and disadvantages

All three tools follow the four steps in a standard LCA established by the International Organization for Standardization (ISO) in ISO 14040 and 14044 (ISO 1997, ISO 2006). However, the different LCA tools varied significantly in the possibility of their use in early design and decision-making. For example, while ATHENA's Impact Estimator and PRé's SimaPro rely on a bill of materials that changes constantly in design alteration Kieran Timberlake's Tally allows for adjustment for these changes and so can be integrated from the beginning of the design process. Table 5 summarizes perceived advantages and disadvantages of each application for the five key criteria.

Table 5. Perceived advantages and disadvantages of the three tools used in the study

(darker means greater advantages)

LCA tool / Comparison component	Integrated with design	Transparency	Building Systems*	Geographical area	LCA Experience
Athena Impact Estimator for Buildings	▒	░	▒	░	▓
Kieran Timberlake's Tally	▓	░	░	▒	▓
PRé SimaPro	░	▓	▓	▒	░

* Building systems that can be included in the LCA: structural, architectural, finishes, mechanical, electrical, and plumbing.

Integration with Design. As mentioned earlier, Tally was the most powerful among the three tools as it is fully integrated with design in the BIM environment. The user needs to link the materials in the BIM environment to the materials database in Tally. For example, different layers in the walls sections (i.e. brick, insulation, CMU, drywall) must be linked to the specific materials in the Tally database (i.e., specify the type of brick or insulation, etc.). Any changes in the building design can be accounted for in the Tally integrated BIM/LCA and also can be compared with the previous design. Tally at this point gives the designer a great opportunity to directly make decisions and make changes based on the LCA results. Although most BIM environments provide solutions for modeling and calculation of the energy consumed in the building's design, Tally depends on the manual data entry of linking materials from BIM to Tally. In contrast, Athena and SimaPro rely on a completed bill of materials so that the designer can then start conducting the LCA analysis. This makes the analysis process isolated from the design process. Although Athena provides a template for the process of exporting and importing from the BIM environment, it is still a time-consuming procedure.

Transparency. SimaPro is the most powerful tool in this area, allowing the user to see the inputs and outputs for all processes. It gives users the ability to participate in the development of the LCA model, passing through the four main phases of LCA, from goal and scope, to life cycle inventory, to life cycle impact assessment, and finally to interpretation. In Athena and Tally, users cannot participate or go through the experience of those four phases; the LCA results are generated directly after the elements of the building have been entered into the tool. There is a tradeoff between simplification and transparency of results. Specifically, it is important to have access to a full view of the supply chain in LCA results so that identification of hotspots can be made.

Building Systems. Athena and SimaPro have the advantage in this area. In Athena and SimaPro users can model any system, as long as it is possible to identify materials and takeoff quantity. In some cases (such as with the case study building), a building contains a large amount of plumbing and ductwork or advanced systems that are neglected despite the presence of design decisions and the possibility of LCA utilization. Tally, however, limits its scope of the analysis to cover the building's architectural, structural, and finish systems. There is no way to add any other systems or products if it is not already recognized by Tally. Including all systems and products, such as structural, architectural, finishes, mechanical, electrical, and plumbing, are important to support system thinking and integrated design approaches.

Geographical Area. All three tools are lacking in this area. This is because it is typical for LCI data and LCIA approaches to represent a geographic region or the country of origin. For example, with LCIA methodologies, TRACI which was designed for North America. Also, tools are often country-centric, for example, Athena (Canada), Gabi (Germany), TEAM (France), LCAiT (Sweden). Some software programs, like SimaPro and Gabi, were designed so that they can handle an unlimited number of LCI databases and LCIA methodologies and so they can add in data from external sources, such as the Ecoinvent database. This is somewhat better, but the challenge which concerns us in this chapter is since GBRS are currently evolving and undergoing international expansion, the application of whole-building LCA is difficult, particularly in developing countries, where the expected growth in the number of buildings is larger. Therefore, all three tools have limitations in this area.

LCA Experience. Athena and Tally require minimal training and the design team can likely use them. For example, in Tally, results are displayed in terms and concepts that building professionals can understand, like the use of (Construction Specifications Institute) CSI's MasterFormat. Athena displays the results of all the building elements divided by the environmental category and the building life cycle stage (Embedded/Operational). SimaPro on the other hand, displays the results divided by the environmental category but does not recognize the building life cycle stages. In cases such as this one, SimaPro requires users to have more experience, adding to its cost. Because of their ease of use, Athena and Tally may improve the deployment of LCA in the building design and construction industry.

5.4.2 Case Study LCA Results

The results of the whole building LCAs for Magee-Womens Hospital (MWH) provide an important opportunity for decision-makers to modify the design according to the LCA results. The LCA results indicate that the impact of LCA software is dependent on the impact category and the precision in the process of materials quantities take-off. The results can be split into two main parts: pre-occupancy environmental impact (Figure 14) and operational environmental impact (Figure 15). Embedded impact covers the building's construction materials and assemblies (pre and post occupancy) while operational impact covers the building's energy consumption (during occupancy).

Pre-Occupancy Environmental Impact. Figure 14 represents the pre-occupancy environmental impacts of the case study building using Tally, Athena, and SimaPro. The LCA results in this figure cover the entire building, including the complete architectural, structural, and finish systems of MWH. The figure has three panels representing three different impact categories: Global Warming Potential (required by LEED), Acidification Potential, and Eutrophication Potential. The stacked columns represent different materials in the building, grouped by (Construction Specifications Institute) CSI's MasterFormat. Figure 14 shows that the variation among the three different tools was greater than the 10% required by LEED, highlighting the goal of this chapter. The results of the grouped CSI's MasterFormat were relatively close as a percentage of total impact. However, as a total, results varied significantly.

The results from SimaPro were the highest, followed by Athena and then Tally. For example, in the Global Warming Potential category, the results were 30,050 for SimaPro, 28,050 for Athena and 31,050 for Tally, all in metric tons of CO_2 equivalent and over the life-cycle of the building. While concrete and masonry represent approximately 65% of the total mass of the building, significant impacts came from fenestrations, metals and finishes – illustrating the importance of using LCA. In the case study building, finishes represent 29% of global warming potential, while the structural system represents only 17% of both impact categories. As shown in Figure 14, openings represent 1.5% only of the total mass of the building, but they represent 9% of the global warming potential. On the other hand, when considering the results from the point of the life-cycle stage, we can see that about 77% of global warming potential and 69% of the primary energy demand will occur during the manufacturing stage, compared to 23% and 31% during the maintenance and replacement, respectively.

The results may be interpreted with two lenses. While in all three tools (Tally, Athena and SimaPro) the LCIA method (TRACI) was used, there were many differences between the LCI databases in terms of the source of the data, the date of the updates and the geographical area represented. On the other hand, the effort in matching the inputs in the three tools (in terms of the quantities and the type of construction materials) to represent the same case study resulted in a relatively close distribution of the results over different group of materials.

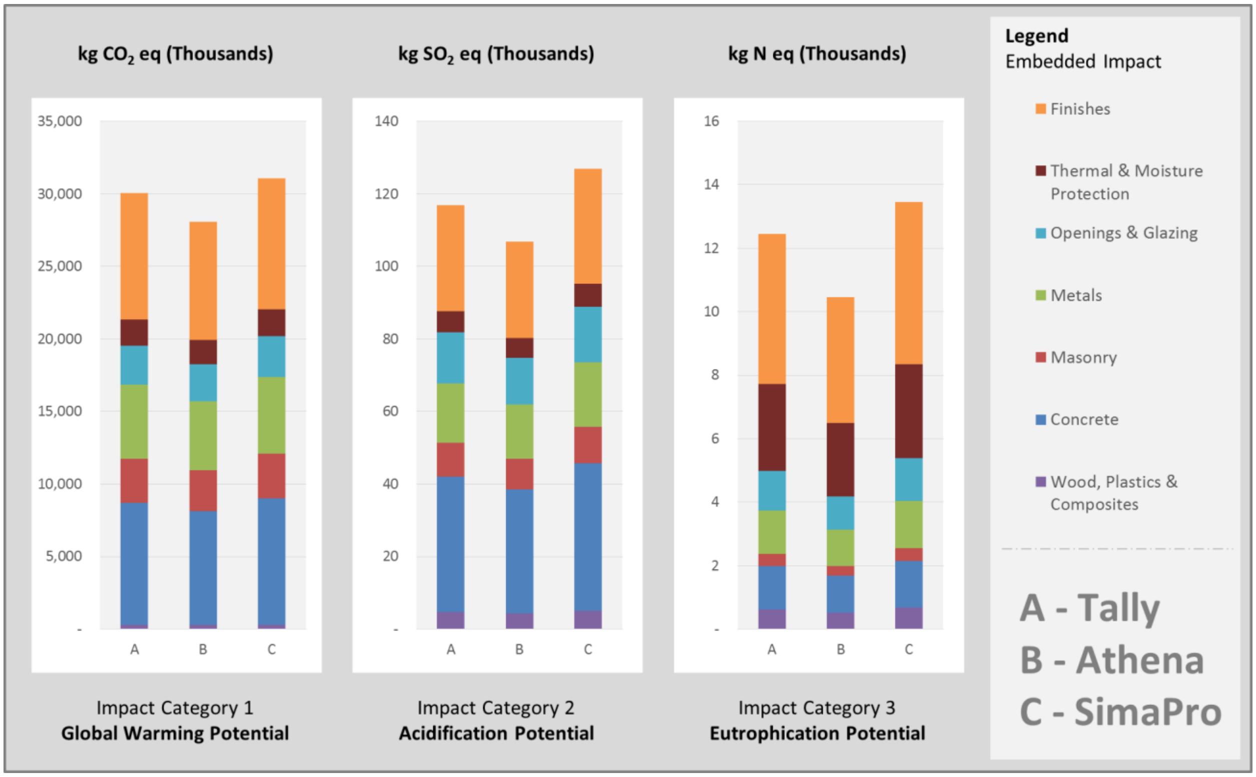


Figure 14. Pre-occupancy environmental impact of the case study building comparing Tally, Athena, and SimaPro. The results in this figure cover the entire building, including complete architectural, structural, and finish systems of Magee-Womens Hospital (MWH). The figure has three panels representing three different impact categories: Global Warming Potential (required by LEED), Acidification Potential, and Eutrophication Potential; impact categories are in different units. The stacked columns represent different materials in the building and are grouped by (Construction Specifications Institute) CSI's MasterFormat.

Operational Environmental Impact. Hospitals have the highest energy consumption per square foot in the buildings sector, annually producing more than 2.5 times the energy intensity and carbon dioxide emissions of commercial office buildings and causing more than 30 pounds of CO_2 emissions per ft^2 (Building Technologies 2008). This high-energy consumption is due to the high space heating, cooling and ventilation loads; the continuous 24 hour operation for the majority of the facilities; and the large amount of medical equipment employed (Balaras, Dascalaki et al. 2007). Figure 15 illustrates the operational environmental impact of MWH as reported by the three different tools, with a comparison of the three environmental impact categories.

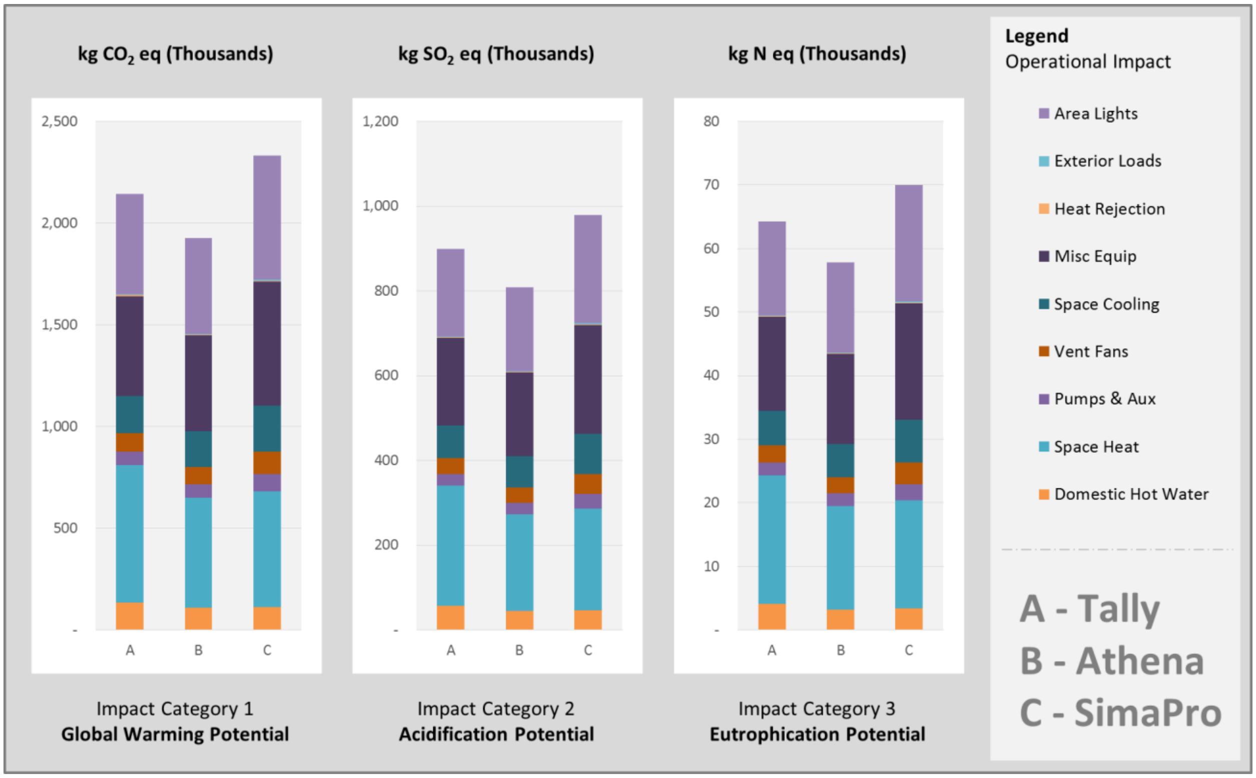


Figure 15. Operational environmental impact of the case study building. The results in this figure cover the operational phase of Magee-Womens Hospital (MWH). The figure has three panels representing three different impact categories, as required by LEED: Global Warming Potential, Acidification Potential, and Eutrophication Potential; the impact categories are in different units as indicated on top of each group of columns. The stacked columns represent different components during operation, such as lighting, HVAC, water heating and pumping. The results here represent real annual consumption of the building as documented through utility bills. The different components on the stacked columns represent the results of the energy simulation model.

Figure 15 also shows that the variation among the three different tools was even greater than the variation in the previous section (i.e., Figure 14). The results varied by about 17%, with the highest numbers again from SimaPro, followed by Tally and then Athena. For example, in the Global Warming Potential category, the results are 2,331,647 for SimaPro, 2,141,800 for Tally and 1,926,000 for Athena, all in annual metric tons of CO_2 equivalent. The comparison here includes the operational phase only, which has fewer variables (inputs and outputs) compared to the pre-occupancy phase. In the case of MWH, the building type (i.e., healthcare building) played a significant role in increasing the percentage of the operational impact compared to the embedded impact. In general in most buildings, 70% to 85% of the environmental impacts are from the use phase. However, in the case of MWH, operational impacts represent 90% to 95% of most of the impact categories.

5.5 CONCLUSION

After creating a building information model (BIM) of a complex building, LCAs were completed using three different software tools, Tally, Athena, and SimaPro, to ascertain the differences between the results and provide guidance for designers and LCA practitioners. The significance of this portion of the research is underscored by the high usage of BIM, with 88% of BIM users surveyed reporting that they expect their firms to use BIM on a green retrofit project (McGraw-Hill Construction 2010). The combination of BIM and LCA can expand the LCA boundary (i.e. including HVAC systems), which can meet the needs of a variety of users in a variety of contexts. Further, potential for integrated energy modeling with BIM can provide the designer with at least a screening tool for energy performance. While the integration between BIM and Tally can truly assist designers in conducting LCAs, there is a level of concern, as with any modeling tool, that the generated ‘black-box’ LCA results have the potential to disconnect the decision-maker from environmental performance because an important value of conducting LCA is uncovering environmental hotspots through deeper LCA interpretation.

The results identified many challenges in the requirements of the various GBRS. One of the most important challenges relates to the comparison with a baseline LCA building with relatively small percentage improvements to obtain credit. The results indicate that given the same building, the LCA results produced by the three software tools varied by 10% in the pre-occupancy impact, as shown in Figure 14, and 17% in the operational impact, as shown in Figure 15. This reinforces the need to not only refine LCA methods for GBRS, but also to obtain more robust datasets for building systems and products. At a minimum, GBRS should include LCA uncertainty analysis into their systems, which some LCA software tools already have.

6.0 CONCLUSIONS

The goal of this dissertation was to quantitatively analyze the potential ability of the green buildings rating systems, such as LEED, to reduce a building's environmental impacts from an international perspective, considering variations climate, energy sources and renewables accessibility. Important results of the dissertation are summarized in this chapter. The outcomes and broader impacts of the research will be presented, followed by the future work and recommendations.

6.1 SUMMARY

Buildings have significant environmental, economic and social impacts on our present and future generations. The impacts for example in the U.S. are about 71% of electricity consumption; 40% of CO_2 emissions; 12% of water use and 65% of waste output. GBRS strive to reduce and control those impacts though many requirements that increase the consumption efficiency of energy, water and materials. A systems approach (i.e., LCA) can assist GBRS to achieve goals in the long and short terms. Applying LCA to GBRS at a systems level, especially rating systems targeting international markets, is critical in understanding and developing thoughtful and meaningful environmental reductions. This research had three main parts that analyzed and made recommendations for the development of GBRS using life-cycle thinking.

The first part investigated the international variations in the energy use and associated environmental life cycle impacts of buildings. A reference BIM model for an office building was developed and placed in 400 locations. LCA was then performed on the buildings' energy consumption. The results varied considerably between the locations in the U.S. (394 ton CO_2 eq) and international (911 ton CO_2 eq) locations, largely due to energy sources. The results show also greater variations in other categories, such as human health and water depletion with respect to the local/regional needs and challenges. The results highlighted the shortcoming of today's GBRS where for example, the potential water depletion due to energy consumption were large in locations that suffer water vulnerability or even scarcity. In contrast, energy related water depletion was small in locations that have an abundance of water. Not only that, other categories like human health impact shows the possibility of buildings to be LEED certified and recognized as green buildings, despite the large variation in the potential human health damage. Since, GBRS are expanding internationally, energy sources for buildings should be considered with a particular suggestion of targeted goals reductions versus aggregated certifications. Using a life-cycle thinking approach in this research showed that location based results with LCA can help to elucidate a better understanding of possible adverse environmental impacts as a result of building energy consumption and efficiency.

The second part of the research extended the part 1 investigation to include renewable on-site energy use and associated environmental life cycle impacts. The same BIM model from part 1 was located in 25 locations. Similar to part 1, energy models were built for each site to compute the solar and wind power produced on-site and available within the building footprint and regional climate. LCA and life cycle cost analysis were then used to analyze the environmental and economic impacts of energy sources (including wind and solar) at each site.

Environmental impacts of renewable energy varied dramatically from one site to another. In some cases, the environmental benefits were limited due to the significant economic burden of those renewable systems on-site and vice versa. Some economic factors (i.e., low cost of electricity) that prevented or reduced the optimum utilization of renewable energy plays a role that cannot be undervalued. The requirements in toddy's LEED rating system show a disconnect with the international trends regarding renewable energy. Several international organizations show an optimistic view and higher expectations of renewable energy utilization in the future, especially in buildings. The requirements of renewable energy generation in existing GBRS need to be developed and changed to be a percentage of what is actually available on-site, instead of a fixed percentage of the energy needed by the building. Likewise, buildings with higher environmental impacts due to the type of conventional energy sources should be required to achieve higher levels of renewable utilization based on associated impacts. Finally, GBRS need more detailed requirements for different renewable energy technologies. This study shows considerable variations in the economic and the environment impacts of different technologies; the wind power (turbines) shows very limited benefits for the case study building compared to solar (PVs).

Finally for part 3, a comparative analysis of three whole building LCA tools (Athena Impact Estimator for Buildings, Tally and SimaPro) was conducted to provide guidance to LCA practitioners and designers. The software tools vary in key aspects such as intended users (e.g., LCA experts or novices), design stage, and time. The comparative LCA results indicate that the impact of LCA software is dependent on the impact category and the precision in the process of material quantity take-offs. One of the most important challenges is a comparison with a baseline LCA building with relatively small percentage improvements to obtain credits. The results indicated that given the same building, the LCA results varied by about 10% in the pre-occupancy impact to 17% in the operational impact in the impact categories selected. This reinforces the need to not only refine LCA methods for GBRS, but also work towards robust data sets for building systems and products. At a minimum, GBRS should include LCA uncertainty analysis into their systems. GBRS also should consider the technologies available in the market today that support synergies and interconnectedness in the building design process. This research showed that while the integration between BIM and LCA using Tally can truly assist designers in conducting LCAs, there is a level of concern, as with any modeling tools, that the generated ‘black-box’ LCA results have the potential to disconnect the decision maker with environmental performance because an important value of conducting LCA is uncovering environmental hotspots through deeper LCA interpretation.

6.2 OUTCOMES AND BROADER IMPACTS

Given the research conducted herein and in the context of GBRS, the results confirm that energy sources and associated environmental impacts matter significantly. Since GBRS such as LEED are currently undergoing international expansion, consideration of energy sources for buildings should be reflected in future GBRS revisions, with a particular suggestion of targeted goals versus aggregated certifications. The results revealed that location specific results, when paired with LCA, can be an effective means to achieve a better understanding and reduction of the adverse environmental impacts resulting from energy consumption.

Findings particularly significant given the fact that the LEED system has rapidly expanded into a global system to cover most of the world. In 2013, about 4,900 cities were registered with green building profiles on the USGBC's Green Building Information Gateway (GBIG 2013). Today there are more than 10 billion square feet of building space certified by LEED. Also, 1.5 million square feet get certified each day in 135 countries (USGBC 2013b). With tremendous benefits on many of the challenges that we face today, where for example, seventy to ninety percent of the environmental impact categories occur in the use phase.

6.3 FUTURE WORK

The emphasis of this dissertation (especially in chapters 3 and 4) was on buildings' external environmental issues without considering the relationship with ambient air and indoor air quality. Indoor air quality is an important element and future work needs to expand the scope of these analyses to include IAQ. As it was discussed in Chapter 5, if GBRS require whole-building LCA, then it is important to develop a standardized, robust and reliable specification that creates comparable LCA results for buildings. Future work also involve extending the approach developed during this dissertation to different data types, exploration of additional high performance building case studies, and systems in the built environment.

Many other important categories like water was examined briefly Chapter 3 and in the context of energy consumption only. Water related issues particularly in developing countries represent a big challenge. Using a life-cycle thinking approach to assess and improve GBRS in water efficiencies can be an import future work.

Different on-site renewable energy systems show considerable variations in their economic and the environment impacts. The wind power (turbines) for example in Chapter 4, show very limited benefits for the case study building compared to the solar (PVs). The variations here highlighted the need for future work that examine various renewable energy technologies and how can GBRS maximum the environmental, economic and social benefit.

Before GBRS can fully integrate LCA in the process of building design, the appropriate tools should be provided to professionals to aid them in the evaluation of the building design. That evaluation should be in a way that accurately accounts for the impacts of the entire life-cycle of the building in all building phases, while not neglecting any important LCA uncertainty.

APPENDIX A

SUPPLEMENTARY DATA FOR ENERGY AND LCA MODELING

The following is supplementary information for chapter 3. It comprises all simulation and modeling data for all sites (400) included in the study. The tables below show the national sample data followed by the international sample data. The order of the sample sites (both national and international) is in accordance with the original random drawing and the site ID has not changed at any stage of the study or in the references to it throughout chapter 3.

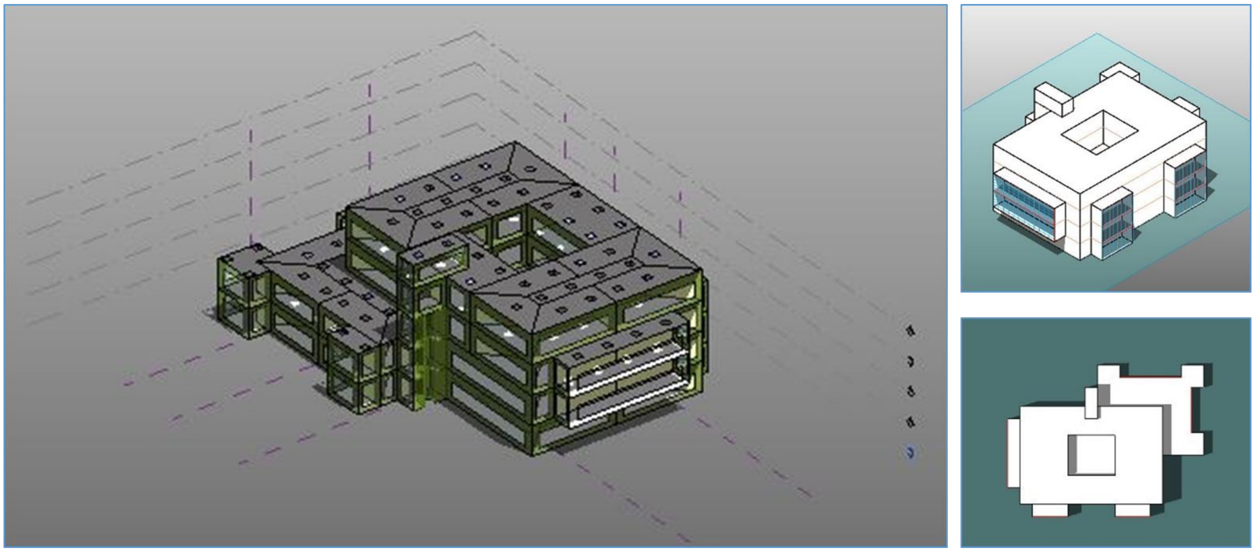


Figure 16. BIM Model of the Case Study Building

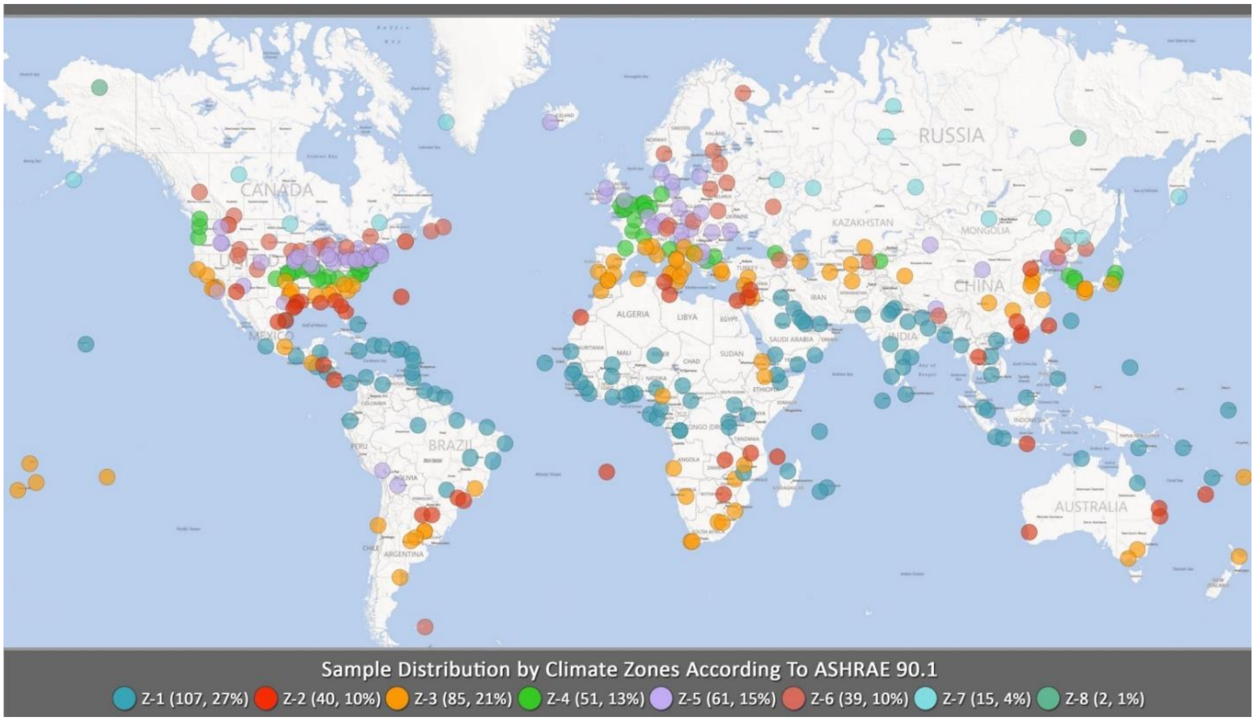


Figure 17. Sample Distribution by Climate Zones

Building Water Usage

To calculate the building water usage the USGBC Indoor Water Use Reduction Calculator was used. The calculator determines the baseline annual consumption based on baseline fixtures and fittings. To determine the minimum number of required plumbing fixtures the 2012 Uniform Plumbing Code (UPC) of the IAPMO was used. UPC is used widely in U.S. and many countries around the world. According to the LEED Calculator, the building will consume 620,500 gallons per year; that usage was held constant in all locations as the building is the same type and has the same number of users. After that, the amount of water that could be potentially recovered by the building at each location was estimated. The recoverable amount includes rainwater harvesting on catchment areas of the building and greywater reclamation for outdoor usage. The rainwater harvesting was calculated based on annual rainfall and a catchment area of 13394 ft^2 (building entire roof). Greywater reclamation was calculated based on data from AWWA.

In Figure 8:

The blue columns represent potential water depletion because of building energy use (m^3); calculated using ReCiPe. The red columns represent LEED annual baseline building water usage; 620,500 gallons per year (2,349 m^3); this is constant in all locations as the building is the same type and has the same number of users. This number does not include life-cycle impacts for water production. It only represents consumption by end-user.

- The shaded area within the red columns shows the percentage that can potentially be saved through rainwater harvesting and greywater reclamation.
- Rainwater harvesting was calculated based on annual rainfall and a catchment area of 13,394 ft^2 (building entire roof).
- Greywater reclamation was calculated according to the American Water Works Association (AWWA) (Dziegielewski 2000).
- The purple line with markers represents the water availability per capita (m^3) in each country from United Nations' World Water Assessment Program (WWAP) (UNESCO 2014).

Table 6. National Sites - Energy Use, Environmental and Human Health Impacts

Figures Rfe. ID	Project ID	Locations Info	ASHREA Climate Zone		Annual Energy kBtu (millions)	Greenhouse Gases Eq CO_2 (Metric Tons)	Human Health (DALY)	Water Depletion (m3)
001	Nat'l-001	Great Falls, VA 22066	4	A	3.18	457	1.00	2,989
002	Nat'l-002	Dubuque, IA 52002	5	A	3.58	614	1.36	2,343
003	Nat'l-003	Westphalia, MI 48894	5	A	3.57	660	1.45	2,486
004	Nat'l-004	Rockton, PA 15856	6	A	3.49	434	0.90	2,688
005	Nat'l-005	Forest Park, GA 30297	3	A	2.88	547	1.20	2,357
006	Nat'l-006	Wayan, ID 83285	6	B	4.14	437	0.85	1,006
007	Nat'l-007	Neosho, WI 53059	6	A	3.62	623	1.37	2,701
008	Nat'l-008	Houston, TX 77011	2	A	2.74	546	1.14	1,993
009	Nat'l-009	Alcolu, SC 29001	3	A	2.88	449	1.02	3,198
010	Nat'l-010	Silverdale, WA 98383	4	C	3.11	355	0.73	962
011	Nat'l-011	Stoneville, SD 57787	6	A	3.77	634	1.39	2,385
012	Nat'l-012	Windmill Point, VA 22578	4	A	2.93	433	0.96	2,920
013	Nat'l-013	Guy, TX 77444	2	A	2.75	542	1.12	1,965
014	Nat'l-014	Pinon Hills, CA 92372	3	B	3.07	374	0.68	1,307
015	Nat'l-015	Plainview, NY 11803	4	A	3.30	486	0.85	683
016	Nat'l-016	Berthoud, CO 80513	5	B	3.38	683	1.48	1,941
017	Nat'l-017	Ola, ID 83657	5	B	3.77	410	0.82	1,011
018	Nat'l-018	Pilot Point, AK 99648	7	-	3.56	295	0.53	357
019	Nat'l-019	Eidson, TN 37731	4	A	3.05	538	1.20	2,499
020	Nat'l-020	Clarion, IA 50525	6	A	3.70	626	1.38	2,367
021	Nat'l-021	Kane, IL 62054	5	A	3.29	676	1.54	2,813
022	Nat'l-022	Winton, CA 95388	3	B	2.90	361	0.67	1,308
023	Nat'l-023	Kila, MT 59920	6	B	3.76	406	0.80	985
024	Nat'l-024	Angus, MN 56762	7	A	4.27	656	1.40	2,281
025	Nat'l-025	Midpark, OH 44130	5	A	3.44	614	1.37	2,738
026	Nat'l-026	Ina, IL 62846	4	A	3.19	674	1.54	2,847
027	Nat'l-027	Ipswich, MA 01938	5	A	3.38	366	0.67	1,717
028	Nat'l-028	Waterbury, CT 06708	5	A	3.41	375	0.69	1,821
029	Nat'l-029	Balko, OK 73931	4	B	3.24	655	1.40	1,793
030	Nat'l-030	Donna, TX 78537	2	A	2.66	552	1.16	2,060
031	Nat'l-031	Newport, PA 17074	5	A	3.34	428	0.90	2,785
032	Nat'l-032	Burkeville, TX 75932	2	A	2.83	538	1.11	1,910
033	Nat'l-033	Ludlow Falls, OH 45339	5	A	3.38	612	1.37	2,760
034	Nat'l-034	Liberty, IL 62347	5	A	3.35	675	1.53	2,778
035	Nat'l-035	Farragut, IA 51639	5	A	3.44	616	1.38	2,420
036	Nat'l-036	Kingdom City, MO 65262	4	A	3.26	673	1.53	2,811
037	Nat'l-037	Baldwin, MI 49304	6	A	3.70	660	1.44	2,435
038	Nat'l-038	Moscow, TX 75960	2	A	2.83	450	0.91	2,256
039	Nat'l-039	Nathrop, CO 81236	6	B	3.88	689	1.45	1,810
040	Nat'l-040	Los Angeles, CA 90042	3	B	2.46	317	0.59	1,214
041	Nat'l-041	Frisco, TX 75034	3	A	2.97	558	1.15	1,969
042	Nat'l-042	Westphalia, KS 66093	4	A	3.24	662	1.49	2,585
043	Nat'l-043	Knob Lick, KY 42154	4	A	3.06	544	1.22	2,536
044	Nat'l-044	Holbrook, AZ 86025	5	B	3.19	531	1.10	2,046
045	Nat'l-045	Logan, UT 84321	6	B	3.73	407	0.81	1,012
046	Nat'l-046	Dexter, IA 50070	5	A	3.53	622	1.38	2,392
047	Nat'l-047	Newhall, CA 91321	3	B	2.52	320	0.59	1,190
048	Nat'l-048	Cornelius, OR 97113	4	C	3.16	360	0.74	959
049	Nat'l-049	South Orange, NJ 07079	4	A	3.31	428	0.90	2,811
050	Nat'l-050	Valencia, PA 16059	5	A	3.38	429	0.89	2,736

Table 6. (continued)

Figures Rfe. ID	Project ID	Locations Info	ASHREA Climate Zone		Annual Energy kBtu (millions)	Greenhouse Gases Eq CO_2 (Metric Tons)	Human Health (DALY)	Water Depletion (m3)
051	Nat’l-051	Loyal, OK 73756	3	A	3.13	650	1.39	1,803
052	Nat’l-052	Hamilton, NJ 08609	5	A	2.88	423	0.94	3,259
053	Nat’l-053	Edwardsburg, MI 49112	5	A	3.49	657	1.45	2,506
054	Nat’l-054	Midlothian, TX 76065	3	A	2.96	558	1.15	1,972
055	Nat’l-055	Clayville, RI 02815	5	A	2.43	297	0.58	1,777
056	Nat’l-056	Hubbardston, MA 01452	5	A	3.57	385	0.71	1,794
057	Nat’l-057	Norman Park, GA 31771	2	A	2.79	566	1.26	2,534
058	Nat’l-058	Onset, MA 02558	5	A	3.49	382	0.70	1,839
059	Nat’l-059	Merrill, IA 51038	6	A	3.62	625	1.38	2,395
060	Nat’l-060	Stedman, NC 28391	3	A	2.91	445	1.00	3,123
061	Nat’l-061	Sappington, MO 63127	4	A	3.23	681	1.56	2,872
062	Nat’l-062	State College, PA 16801	5	A	3.43	611	1.36	2,723
063	Nat’l-063	Hughesville, MD 20637	4	A	3.16	422	0.90	2,889
064	Nat’l-064	Gastonia, NC 28054	3	A	2.93	442	0.99	3,049
065	Nat’l-065	Lancaster, VA 22503	4	A	2.94	433	0.96	2,924
066	Nat’l-066	Mobile, AL 36603	2	A	2.70	555	1.24	2,498
067	Nat’l-067	Cresco, PA 18326	5	A	3.53	438	0.90	2,702
068	Nat’l-068	Camp Hill, AL 36850	3	A	2.93	567	1.25	2,471
069	Nat’l-069	Malaga, NJ 08328	4	A	3.29	429	0.91	2,844
070	Nat’l-070	Cocoa, FL 32926	2	A	2.55	502	1.02	1,845
071	Nat’l-071	Madden, MS 39109	3	A	2.92	563	1.28	2,767
072	Nat’l-072	Fulton, KY 42041	4	A	3.05	550	1.23	2,589
073	Nat’l-073	Chase City, VA 23924	4	A	3.00	444	0.99	2,999
074	Nat’l-074	Maywood, NJ 07607	5	A	3.31	427	0.90	2,799
075	Nat’l-075	Annapolis, CA 95412	3	C	2.83	337	0.61	1,136
076	Nat’l-076	Dorchester, MA 02122	5	A	3.40	369	0.68	1,740
077	Nat’l-077	Honokaa, HI 96727	1	A	2.27	432	0.90	841
078	Nat’l-078	Newton, KS 67114	4	A	3.26	674	1.52	2,647
079	Nat’l-079	Midvale, ID 83645	5	B	3.57	398	0.81	1,035
080	Nat’l-080	Washington, DC 20008	4	A	3.19	425	0.90	2,897
081	Nat’l-081	North Branch, NY 12766	6	A	3.69	318	0.59	1,716
082	Nat’l-082	Fort Wayne, IN 46807	5	A	3.44	618	1.38	2,769
083	Nat’l-083	Jamestown, PA 16134	5	A	3.44	610	1.35	2,707
084	Nat’l-084	Fairfax, MO 64446	5	A	3.41	683	1.54	2,804
085	Nat’l-085	Camarillo, CA 93010	3	C	2.35	301	0.56	1,135
086	Nat’l-086	Hendrix, OK 74741	3	A	2.89	630	1.36	1,793
087	Nat’l-087	Kingston Springs, TN 37082	4	A	2.97	543	1.22	2,576
088	Nat’l-088	Starke, FL 32091	2	A	2.75	516	1.03	1,841
089	Nat’l-089	Anaktuvuk Pass, AK 99721	8	-	3.70	306	0.55	366
090	Nat’l-090	Eureka, KS 67045	4	A	3.25	667	1.50	2,611
091	Nat’l-091	Mountain Lakes, NJ 07046	5	A	3.38	431	0.90	2,773
092	Nat’l-092	Caguas, PR 00726	1	A	2.61	643	1.33	1,177
093	Nat’l-093	Wichita, KS 67220	4	A	3.22	672	1.52	2,656
094	Nat’l-094	Red Oak, IA 51566	5	A	3.50	617	1.37	2,400
095	Nat’l-095	Sheboygan, WI 53081	6	A	3.67	634	1.39	2,385
096	Nat’l-096	Mora, MO 65345	4	A	3.22	672	1.53	2,823
097	Nat’l-097	Proctor, MT 59929	6	B	3.69	401	0.80	991
098	Nat’l-098	Sodus, NY 14551	5	A	3.50	302	0.57	1,663
099	Nat’l-099	Phoenix, AZ 85051	2	B	2.70	522	1.12	2,242
100	Nat’l-100	Medimont, ID 83842	5	B	3.54	391	0.78	992

Table 7. National Sites - Electric Power Plant Sources Details

ID	Locations Info	Fossil	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Nat’l-001	Great Falls, VA 22066	54.70%	45.10%	0.60%	9.00%	41.30%	1.60%	2.00%	0.40%
Nat’l-002	Dubuque, IA 52002	71.70%	69.10%	0.20%	2.40%	13.90%	4.40%	9.80%	0.20%
Nat’l-003	Westphalia, MI 48894	81.90%	72.00%	0.40%	9.50%	15.30%	0.00%	2.20%	0.60%
Nat’l-004	Rockton, PA 15856	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-005	Forest Park, GA 30297	74.80%	52.20%	0.30%	22.30%	18.10%	4.10%	2.90%	0.10%
Nat’l-006	Wayan, ID 83285	45.30%	29.80%	0.30%	15.20%	2.50%	46.50%	5.40%	0.30%
Nat’l-007	Neosho, WI 53059	73.80%	69.90%	0.40%	3.50%	23.60%	0.80%	1.40%	0.40%
Nat’l-008	Houston, TX 77011	81.90%	33.00%	1.10%	47.80%	12.30%	0.20%	5.50%	0.10%
Nat’l-009	Alcolu, SC 29001	54.70%	45.10%	0.60%	9.00%	41.30%	1.60%	2.00%	0.40%
Nat’l-010	Silverdale, WA 98383	45.30%	29.80%	0.30%	15.20%	2.50%	46.50%	5.40%	0.30%
Nat’l-011	Stoneville, SD 57787	71.70%	69.10%	0.20%	2.40%	13.90%	4.40%	9.80%	0.20%
Nat’l-012	Windmill Point, VA 22578	54.70%	45.10%	0.60%	9.00%	41.30%	1.60%	2.00%	0.40%
Nat’l-013	Guy, TX 77444	81.90%	33.00%	1.10%	47.80%	12.30%	0.20%	5.50%	0.10%
Nat’l-014	Pinon Hills, CA 92372	61.70%	7.30%	1.40%	53.00%	14.90%	12.70%	10.10%	0.60%
Nat’l-015	Plainview, NY 11803	90.30%	0.00%	13.00%	77.30%	0.00%	0.00%	5.10%	4.60%
Nat’l-016	Berthoud, CO 80513	90.40%	67.80%	0.00%	22.60%	0.00%	4.30%	5.20%	0.10%
Nat’l-017	Ola, ID 83657	45.30%	29.80%	0.30%	15.20%	2.50%	46.50%	5.40%	0.30%
Nat’l-018	Pilot Point, AK 99648	35.20%	0.00%	31.30%	3.90%	0.00%	63.90%	1.00%	0.00%
Nat’l-019	Eidson, TN 37731	68.30%	58.80%	0.90%	8.60%	22.10%	8.60%	0.90%	0.10%
Nat’l-020	Clarion, IA 50525	71.70%	69.10%	0.20%	2.40%	13.90%	4.40%	9.80%	0.20%
Nat’l-021	Kane, IL 62054	80.90%	79.80%	0.10%	1.00%	17.10%	1.80%	0.20%	0.00%
Nat’l-022	Winton, CA 95388	61.70%	7.30%	1.40%	53.00%	14.90%	12.70%	10.10%	0.60%
Nat’l-023	Kila, MT 59920	45.30%	29.80%	0.30%	15.20%	2.50%	46.50%	5.40%	0.30%
Nat’l-024	Angus, MN 56762	71.70%	69.10%	0.20%	2.40%	13.90%	4.40%	9.80%	0.20%
Nat’l-025	Midpark, OH 44130	73.80%	69.90%	0.40%	3.50%	23.60%	0.80%	1.40%	0.40%
Nat’l-026	Ina, IL 62846	80.90%	79.80%	0.10%	1.00%	17.10%	1.80%	0.20%	0.00%
Nat’l-027	Ipswich, MA 01938	55.40%	11.90%	1.50%	42.00%	29.80%	7.00%	6.20%	1.60%
Nat’l-028	Waterbury, CT 06708	55.40%	11.90%	1.50%	42.00%	29.80%	7.00%	6.20%	1.60%
Nat’l-029	Balko, OK 73931	89.30%	55.20%	0.20%	33.90%	0.00%	5.50%	5.00%	0.20%
Nat’l-030	Donna, TX 78537	81.90%	33.00%	1.10%	47.80%	12.30%	0.20%	5.50%	0.10%
Nat’l-031	Newport, PA 17074	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-032	Burkeville, TX 75932	81.90%	33.00%	1.10%	47.80%	12.30%	0.20%	5.50%	0.10%
Nat’l-033	Ludlow Falls, OH 45339	73.80%	69.90%	0.40%	3.50%	23.60%	0.80%	1.40%	0.40%
Nat’l-034	Liberty, IL 62347	80.90%	79.80%	0.10%	1.00%	17.10%	1.80%	0.20%	0.00%
Nat’l-035	Farragut, IA 51639	71.70%	69.10%	0.20%	2.40%	13.90%	4.40%	9.80%	0.20%
Nat’l-036	Kingdom City, MO 65262	80.90%	79.80%	0.10%	1.00%	17.10%	1.80%	0.20%	0.00%
Nat’l-037	Baldwin, MI 49304	81.90%	72.00%	0.40%	9.50%	15.30%	0.00%	2.20%	0.60%
Nat’l-038	Moscow, TX 75960	69.30%	22.70%	1.50%	45.10%	26.00%	1.70%	1.90%	1.10%
Nat’l-039	Nathrop, CO 81236	90.40%	67.80%	0.00%	22.60%	0.00%	4.30%	5.20%	0.10%
Nat’l-040	Los Angeles, CA 90042	61.70%	7.30%	1.40%	53.00%	14.90%	12.70%	10.10%	0.60%
Nat’l-041	Frisco, TX 75034	81.90%	33.00%	1.10%	47.80%	12.30%	0.20%	5.50%	0.10%
Nat’l-042	Westphalia, KS 66093	81.90%	73.80%	0.30%	7.80%	13.50%	0.10%	4.40%	0.10%
Nat’l-043	Knob Lick, KY 42154	68.30%	58.80%	0.90%	8.60%	22.10%	8.60%	0.90%	0.10%
Nat’l-044	Holbrook, AZ 86025	74.30%	38.50%	0.10%	35.70%	16.50%	6.10%	3.10%	0.00%
Nat’l-045	Logan, UT 84321	45.30%	29.80%	0.30%	15.20%	2.50%	46.50%	5.40%	0.30%
Nat’l-046	Dexter, IA 50070	72.70%	69.10%	1.20%	2.40%	13.90%	4.40%	9.00%	0.00%
Nat’l-047	Newhall, CA 91321	61.70%	7.30%	1.40%	53.00%	14.90%	12.70%	10.10%	0.60%
Nat’l-048	Cornelius, OR 97113	45.30%	29.80%	0.30%	15.20%	2.20%	46.50%	5.40%	0.60%
Nat’l-049	South Orange, NJ 07079	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-050	Valencia, PA 16059	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%

Table 7. (continued)

ID	Locations Info	Fossil	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Nat’l-051	Great Falls, VA 22066	89.30%	55.20%	0.20%	33.90%	0.00%	5.50%	5.00%	0.20%
Nat’l-052	Dubuque, IA 52002	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-053	Westphalia, MI 48894	81.90%	72.00%	0.40%	9.50%	15.30%	0.00%	2.20%	0.60%
Nat’l-054	Rockton, PA 15856	81.90%	33.00%	1.10%	47.80%	12.30%	0.20%	5.50%	0.10%
Nat’l-055	Forest Park, GA 30297	55.40%	11.90%	1.50%	42.00%	29.80%	7.00%	6.20%	1.60%
Nat’l-056	Wayan, ID 83285	55.40%	11.90%	1.50%	42.00%	29.80%	7.00%	6.20%	1.60%
Nat’l-057	Neosho, WI 53059	74.80%	52.20%	0.30%	22.30%	18.10%	4.10%	2.90%	0.10%
Nat’l-058	Houston, TX 77011	55.40%	11.90%	1.50%	42.00%	29.80%	7.00%	6.20%	1.60%
Nat’l-059	Alcolu, SC 29001	71.70%	69.10%	0.20%	2.40%	13.90%	4.40%	9.80%	0.20%
Nat’l-060	Silverdale, WA 98383	54.70%	45.10%	0.60%	9.00%	41.30%	1.60%	2.00%	0.40%
Nat’l-061	Stoneville, SD 57787	80.90%	79.80%	0.10%	1.00%	17.10%	1.80%	0.20%	0.00%
Nat’l-062	Windmill Point, VA 22578	73.80%	69.90%	0.40%	3.50%	23.60%	0.80%	1.40%	0.40%
Nat’l-063	Guy, TX 77444	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-064	Pinon Hills, CA 92372	54.70%	45.10%	0.60%	9.00%	41.30%	1.60%	2.00%	0.40%
Nat’l-065	Plainview, NY 11803	54.70%	45.10%	0.60%	9.00%	41.30%	1.60%	2.00%	0.40%
Nat’l-066	Berthoud, CO 80513	74.80%	52.20%	0.30%	22.30%	18.10%	4.10%	2.90%	0.10%
Nat’l-067	Ola, ID 83657	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-068	Pilot Point, AK 99648	74.80%	52.20%	0.30%	22.30%	18.10%	4.10%	2.90%	0.10%
Nat’l-069	Eidson, TN 37731	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-070	Clarion, IA 50525	82.90%	23.70%	4.40%	54.80%	14.00%	0.00%	1.70%	1.40%
Nat’l-071	Kane, IL 62054	68.30%	58.80%	0.90%	8.60%	22.10%	8.60%	0.90%	0.10%
Nat’l-072	Winton, CA 95388	68.30%	58.80%	0.90%	8.60%	22.10%	8.60%	0.90%	0.10%
Nat’l-073	Kila, MT 59920	54.70%	45.10%	0.60%	9.00%	41.30%	1.60%	2.00%	0.40%
Nat’l-074	Angus, MN 56762	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-075	Midpark, OH 44130	61.70%	7.30%	1.40%	53.00%	14.90%	12.70%	10.10%	0.60%
Nat’l-076	Ina, IL 62846	55.40%	11.90%	1.50%	42.00%	29.80%	7.00%	6.20%	1.60%
Nat’l-077	Ipswich, MA 01938	71.90%	2.00%	69.90%	0.00%	0.00%	0.37%	17.30%	0.00%
Nat’l-078	Waterbury, CT 06708	81.90%	73.80%	0.30%	7.80%	13.50%	0.10%	4.40%	0.10%
Nat’l-079	Balko, OK 73931	45.30%	29.80%	0.30%	15.20%	2.50%	46.50%	5.40%	0.30%
Nat’l-080	Donna, TX 78537	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-081	Newport, PA 17074	34.30%	14.50%	0.90%	18.90%	30.60%	30.80%	3.90%	0.40%
Nat’l-082	Burkeville, TX 75932	73.80%	69.90%	0.40%	3.50%	23.60%	0.80%	1.40%	0.40%
Nat’l-083	Ludlow Falls, OH 45339	73.80%	69.90%	0.40%	3.50%	23.60%	0.80%	1.40%	0.40%
Nat’l-084	Liberty, IL 62347	80.90%	79.80%	0.10%	1.00%	17.10%	1.80%	0.20%	0.00%
Nat’l-085	Farragut, IA 51639	61.70%	7.30%	1.40%	53.00%	14.90%	12.70%	10.10%	0.60%
Nat’l-086	Kingdom City, MO 65262	89.30%	55.20%	0.20%	33.90%	0.00%	5.50%	5.00%	0.20%
Nat’l-087	Baldwin, MI 49304	68.30%	58.80%	0.90%	8.60%	22.10%	8.60%	0.90%	0.10%
Nat’l-088	Moscow, TX 75960	82.90%	23.70%	4.40%	54.80%	14.00%	0.00%	1.70%	1.40%
Nat’l-089	Nathrop, CO 81236	35.20%	0.00%	31.30%	3.90%	0.00%	63.90%	1.00%	0.00%
Nat’l-090	Los Angeles, CA 90042	81.90%	73.80%	0.30%	7.80%	13.50%	0.10%	4.40%	0.10%
Nat’l-091	Frisco, TX 75034	53.20%	35.40%	0.70%	17.10%	43.00%	1.20%	1.70%	0.90%
Nat’l-092	Westphalia, KS 66093	99.79%	0.00%	99.79%	0.00%	0.00%	0.21%	0.00%	0.00%
Nat’l-093	Knob Lick, KY 42154	81.90%	73.80%	0.30%	7.80%	13.50%	0.10%	4.40%	0.10%
Nat’l-094	Holbrook, AZ 86025	71.70%	69.10%	0.20%	2.40%	13.90%	4.40%	9.80%	0.20%
Nat’l-095	Logan, UT 84321	76.30%	68.90%	2.40%	5.00%	15.30%	2.70%	5.60%	0.10%
Nat’l-096	Dexter, IA 50070	80.90%	79.80%	0.10%	1.00%	17.10%	1.80%	0.20%	0.00%
Nat’l-097	Newhall, CA 91321	45.30%	29.80%	0.30%	15.20%	2.50%	46.50%	5.40%	0.30%
Nat’l-098	Cornelius, OR 97113	34.30%	14.50%	0.90%	18.90%	30.60%	30.80%	3.90%	0.40%
Nat’l-099	South Orange, NJ 07079	74.30%	38.60%	0.10%	35.60%	16.50%	6.10%	3.10%	0.00%
Nat’l-100	Valencia, PA 16059	45.30%	29.80%	0.30%	15.20%	2.50%	46.50%	5.40%	0.30%

Table 8. International Sites - Energy Use, Environmental and Human Health Impacts

Figures Rfe. ID	Project ID	Locations Info	ASHREA Climate Zone		Annual Energy kBtu (millions)	Greenhouse Gases Eq CO_2 (Metric Tons)	Human Health (DALY)	Water Depletion (m3)
101	Int’l-028	Hamilton, British Territory	2	A	2.44	580	1.20	1,048
102	Int’l-050	Waterloo, Canada	6	A	3.76	677	1.42	1,741
103	Int’l-051	Halifax, Canada	6	A	3.69	539	1.11	1,310
104	Int’l-052	Dartmouth, Canada	6	A	3.69	538	1.11	1,307
105	Int’l-053	Lethbridge, Canada	6	A	3.87	207	0.36	339
106	Int’l-054	Terrebonne, Canada	6	A	3.99	176	0.28	139
107	Int’l-055	Langley, Canada	4	C	3.09	284	0.57	662
108	Int’l-056	Fort McMurray, Canada	7	-	4.85	809	1.65	1,909
109	Int’l-057	St. John's, Canada	6	A	3.92	184	0.29	142
110	Int’l-058	Saguenay, Canada	7	-	4.49	212	0.32	126
111	Int’l-059	Prince George, Canada	6	A	4.03	194	0.32	328
112	Int’l-088	San Jose, Costa Rica	2	A	2.48	38	0.07	72
113	Int’l-128	Nuuk, Greenland	7	-	4.52	659	1.24	907
114	Int’l-194	Río Bravo, Mexico	1	A	2.66	596	1.16	1,206
115	Int’l-195	Cholula, Mexico	3	A	2.43	489	0.94	963
116	Int’l-196	Guadalupe, Mexico	2	A	2.53	555	1.08	1,115
117	Int’l-197	Colima, Mexico	1	A	2.62	541	1.06	1,103
118	Int’l-198	Juchitán de zaragoza, Mexico	1	A	2.77	224	0.46	662
119	Int’l-241	Saint-Pierre	6	A	3.87	340	0.62	468
120	Int’l-005	St. John's, Antigua & Barbuda	1	A	2.70	669	1.39	1,229
121	Int’l-006	Venado Tuerto, Argentina	3	A	2.80	516	0.94	850
122	Int’l-007	Concordia , Argentina	3	A	2.55	34	0.06	48
123	Int’l-008	Puerto Madryn, Argentina	3	C	2.76	479	0.87	763
124	Int’l-009	Rosario, Argentina	3	A	2.78	526	0.96	881
125	Int’l-010	Resistencia, Argentina	2	A	2.60	532	0.98	925
126	Int’l-021	Nassau, Bahamas	1	A	2.58	635	1.32	1,163
127	Int’l-026	Belize City, Belize	1	A	2.67	372	0.78	816
128	Int’l-030	Potosí, Bolivia	5	A	2.55	311	0.53	418
129	Int’l-033	Manaus, Brazil	1	A	2.49	641	1.35	1,556
130	Int’l-034	Salvador, Brazil	1	A	2.59	188	0.40	473
131	Int’l-035	Cabo, Brazil	1	A	2.68	538	1.13	1,366
132	Int’l-036	Sobral, Brazil	1	A	2.77	8	0.02	46
133	Int’l-037	Barreiras, Brazil	1	A	2.62	12	0.02	44
134	Int’l-038	Botucatu, Brazil	2	A	2.49	39	0.08	161
135	Int’l-039	Abaetetuba, Brazil	1	A	2.70	699	1.47	1,702
136	Int’l-040	Taboão da Serra, Brazil	2	A	2.46	103	0.21	237
137	Int’l-041	TrÃªs Lagoas, Brazil	1	A	2.64	17	0.03	57
138	Int’l-042	Ouro Preto, Brazil	3	A	2.50	149	0.30	379
139	Int’l-043	Road Ton, British Virgin Islands	1	A	2.68	665	1.38	1,220
140	Int’l-063	Coquimbo, Chile	3	C	2.34	39	0.07	77
141	Int’l-084	Sabanalarga, Colombia	1	A	2.73	662	1.33	1,560
142	Int’l-095	Roseau, Dominica	1	A	2.70	667	1.39	1,224
143	Int’l-096	San F. de M., Dominican Rep.	1	A	2.58	421	0.88	903
144	Int’l-097	Babahoyo, Ecuador	1	A	2.33	469	0.95	847
145	Int’l-099	San Marcos, El Salvador	1	A	2.58	332	0.70	719
146	Int’l-104	Stanley, British Territory	6	A	3.44	515	0.99	771
147	Int’l-114	Cayenne, French Guiana	1	A	2.61	633	1.32	1,170
148	Int’l-129	Saint George's, Grenada	1	A	2.72	676	1.40	1,241
149	Int’l-131	Guatemala City, Guatemala	3	A	2.47	263	0.55	628
150	Int’l-134	Georgeton, Guyana	1	A	2.64	634	1.32	1,173

Table 8. (continued)

Figures Rfe. ID	Project ID	Locations Info	ASHREA Climate Zone		Annual Energy kBtu (millions)	Greenhouse Gases Eq CO_2 (Metric Tons)	Human Health (DALY)	Water Depletion (m3)
151	Int'l-135	Gonaïves, Haiti	1	B	2.57	585	1.21	1,073
152	Int'l-136	Tegucigalpa, Honduras	2	A	2.51	576	1.19	1,036
153	Int'l-162	Spanish Ton, Jamaica	1	A	2.61	600	1.25	1,109
154	Int'l-212	Masaya, Nicaragua	1	A	2.70	513	1.07	1,015
155	Int'l-219	Las Cumbres, Panama	1	A	2.59	463	0.96	858
156	Int'l-221	Encarnación, Paraguay	2	A	2.62	259	0.57	710
157	Int'l-222	Juliaca, Peru	5	A	2.46	425	0.76	693
158	Int'l-266	Paramaribo, Suriname	1	A	2.64	284	0.59	539
159	Int'l-276	Mon Repos, Trinidad & Tobago	1	A	2.68	544	0.95	861
160	Int'l-292	Salto, Uruguay	3	A	2.55	34	0.06	48
161	Int'l-295	Alto Barinas, Venezuela	1	A	2.67	56	0.11	125
162	Int'l-002	Shkodër, Albania	3	C	3.07	79	0.12	66
163	Int'l-019	Innsbruck, Austria	6	A	3.87	278	0.48	375
164	Int'l-024	Polatsk, Belarus	6	A	4.02	565	0.97	722
165	Int'l-025	Liege, Belgium	4	A	3.33	391	0.71	1,847
166	Int'l-031	Bihać, Bosnia & Herzegovina	5	A	3.46	335	0.70	835
167	Int'l-045	Ardino, Bulgaria	4	A	3.35	707	1.58	2,126
168	Int'l-090	Split, Croatia	3	C	2.95	85	0.13	77
169	Int'l-091	Larnaca, Cyprus	3	B	2.55	581	1.19	1,033
170	Int'l-092	Zlín, Czech Republic	5	A	3.69	440	0.94	2,777
171	Int'l-093	Aalborg, Denmark	5	A	3.53	488	1.01	1,242
172	Int'l-102	Tartu, Estonia	6	A	4.05	203	0.34	328
173	Int'l-106	Vantaa, Finland	6	A	4.06	487	0.96	2,463
174	Int'l-107	Ajaccio, France	3	C	2.46	405	0.86	1,083
175	Int'l-108	Nice, France	3	C	2.50	86	0.16	161
176	Int'l-109	Aix-en-Provence, France	3	C	3.03	350	0.71	830
177	Int'l-110	Saint-Denis, France	4	A	3.13	252	0.50	3,040
178	Int'l-111	Villeurbanne, France	4	A	3.24	125	0.23	3,269
179	Int'l-112	Pau, France	4	A	3.03	104	0.17	123
180	Int'l-113	Châteauroux, France	4	A	3.23	117	0.21	3,745
181	Int'l-118	Freiburg, Germany	5	A	3.42	165	0.31	3,102
182	Int'l-119	Eimsbüttel, Germany	4	A	3.39	363	0.75	2,403
183	Int'l-120	Düsseldorf, Germany	4	A	3.31	685	1.48	1,925
184	Int'l-121	Rosenheim, Germany	6	A	3.77	313	0.61	2,461
185	Int'l-122	Görlitz, Germany	5	A	3.58	711	1.53	1,944
186	Int'l-123	Heidenheim, Germany	5	A	3.63	258	0.50	3,237
187	Int'l-124	Stralsund, Germany	5	A	3.51	522	1.10	1,394
188	Int'l-126	Gibraltar, British Territory	3	A	2.37	471	0.97	853
189	Int'l-127	Thessaloniki, Greece	4	A	3.08	670	1.46	1,878
190	Int'l-137	Székesfehérvár , Hungary	5	A	3.46	312	0.60	2,964
191	Int'l-138	Reykjavik, Iceland	5	A	3.15	130	0.20	132
192	Int'l-153	Tallaght, Ireland	5	A	3.19	488	0.92	953
193	Int'l-155	Bagheria, Italy	3	A	2.50	410	0.80	876
194	Int'l-156	Siracusa, Italy	3	B	2.47	440	0.86	928
195	Int'l-157	Caserta, Italy	3	C	3.00	392	0.75	780
196	Int'l-158	Perugia, Italy	4	A	3.18	393	0.74	750
197	Int'l-159	Naples, Italy	3	A	2.83	361	0.69	740
198	Int'l-160	Marsala, Italy	3	B	2.48	224	0.44	527
199	Int'l-161	Catanzaro, Italy	3	C	2.52	454	0.88	937
200	Int'l-177	Liepāja, Latvia	5	A	3.64	392	0.66	533

Table 8. (continued)

Figures Rfe. ID	Project ID	Locations Info	ASHREA Climate Zone		Annual Energy kBtu (millions)	Greenhouse Gases Eq CO_2 (Metric Tons)	Human Health (DALY)	Water Depletion (m3)
201	Int’l-182	Alytus, Lithuania	6	A	3.88	487	0.85	636
202	Int’l-183	Luxembourg, Luxembourg	5	A	3.43	279	0.47	2,340
203	Int’l-185	Prilep, Macedonia	5	A	3.38	743	1.68	2,293
204	Int’l-191	Valletta, Malta	3	B	2.44	555	1.14	986
205	Int’l-199	Tiraspol, Moldova	5	A	3.62	539	0.92	713
206	Int’l-201	Podgorica, Montenegro	4	A	3.19	95	0.15	71
207	Int’l-207	Nieuegein, Netherlands	4	A	3.31	397	0.75	1,848
208	Int’l-208	Dordrecht, Netherlands	4	A	3.27	432	0.82	1,688
209	Int’l-209	Bergen op Zoom, Netherlands	4	A	3.22	438	0.83	1,683
210	Int’l-216	Oslo, Norway	6	A	3.83	159	0.24	97
211	Int’l-224	Mielec, Poland	5	A	3.68	790	1.76	2,363
212	Int’l-225	Odivelas, Portugal	3	A	2.56	526	1.12	1,423
213	Int’l-228	Targu Mures, Romania	5	A	3.55	405	0.83	966
214	Int’l-248	Vranje, Serbia	5	A	3.41	750	1.70	2,343
215	Int’l-252	Banská Bystrica, Slovak Rep.	6	A	3.63	188	0.34	2,848
216	Int’l-253	Maribor, Slovenia	5	A	3.44	393	0.83	2,057
217	Int’l-262	Algeciras, Spain	3	A	2.40	462	0.91	1,019
218	Int’l-263	Latina, Spain	3	C	3.06	443	0.85	908
219	Int’l-264	Jaén, Spain	3	C	2.97	177	0.33	412
220	Int’l-268	Malmö, Sweden	5	A	3.48	551	1.11	1,234
221	Int’l-269	Basel, Switzerland	5	A	3.40	138	0.24	3,173
222	Int’l-278	Menemen, Turkey	3	A	2.61	567	1.15	1,365
223	Int’l-279	Tarsus, Turkey	3	A	2.99	608	1.23	1,451
224	Int’l-280	Söke, Turkey	3	A	2.63	558	1.14	1,354
225	Int’l-283	Rivne, Ukraine	6	A	3.84	157	0.27	3,896
226	Int’l-285	Portsmouth, United Kingdom	4	A	3.03	488	0.97	1,467
227	Int’l-286	Sindon, United Kingdom	4	A	3.25	509	1.00	1,434
228	Int’l-287	Corby, United Kingdom	5	A	3.27	567	1.12	1,245
229	Int’l-288	Horsham, United Kingdom	4	A	3.19	532	1.05	1,411
230	Int’l-289	Castlereagh, United Kingdom	5	A	3.28	525	1.03	1,127
231	Int’l-290	Clacton-on-Sea, UK	4	A	3.07	443	0.87	1,787
232	Int’l-291	Northampton, United Kingdom	4	A	3.27	560	1.10	1,231
233	Int’l-011	Gyumri, Armenia	6	A	3.77	301	0.61	2,606
234	Int’l-020	Baku, Azerbaijan	3	B	3.14	522	0.90	743
235	Int’l-117	Kutaisi, Georgia	4	A	3.21	92	0.14	71
236	Int’l-171	Kentau, Kazakhstan	3	B	3.50	854	1.92	2,601
237	Int’l-175	Osh, Kyrgyz Republic	4	B	3.32	175	0.30	247
238	Int’l-229	Pavlovo, Russia	7	-	4.33	647	1.19	1,135
239	Int’l-230	Berdsk, Russia	7	-	4.82	593	1.07	944
240	Int’l-231	Borisoglebsk, Russia	6	A	4.11	630	1.17	1,130
241	Int’l-232	Petropavlovsk-K., Russia	7	-	4.05	505	0.92	865
242	Int’l-233	Tuymazy, Russia	7	-	4.37	661	1.22	1,177
243	Int’l-234	Vladivostok, Russia	6	A	3.78	604	1.13	1,117
244	Int’l-235	Yakutsk, Russia	8	-	5.53	749	1.35	1,202
245	Int’l-236	Apatity, Russia	6	A	4.15	231	0.39	2,814
246	Int’l-237	Kogalym, Russia	7	-	4.76	687	1.26	1,169
247	Int’l-238	Novyy Urengoy, Russia	7	-	4.85	691	1.26	1,162
248	Int’l-271	Khujand, Tajikistan	6	B	3.82	192	0.30	148
249	Int’l-281	Ashgabat, Turkmenistan	3	B	3.22	549	0.94	791
250	Int’l-293	Kogon, Uzbekistan	3	B	3.32	572	1.01	902

Table 8. (continued)

Figures Rfe. ID	Project ID	Locations Info	ASHREA Climate Zone		Annual Energy kBtu (millions)	Greenhouse Gases Eq CO_2 (Metric Tons)	Human Health (DALY)	Water Depletion (m3)
251	Int’l-003	Bougara, Algeria	3	A	2.59	468	0.81	701
252	Int’l-004	Lubango, Angola	3	A	2.41	310	0.62	529
253	Int’l-027	Cotonou, Benin	1	A	2.64	654	1.36	1,201
254	Int’l-032	Selebi-Phike, Botsana	2	B	2.61	833	1.98	2,916
255	Int’l-046	Bobo-Dioulasso, Burkina Faso	1	A	2.70	665	1.38	1,218
256	Int’l-047	Bujumbura, Burundi	1	A	2.55	30	0.06	80
257	Int’l-049	Mbouda, Cameroon	3	A	2.46	535	1.06	921
258	Int’l-060	Praia, Cape Verde	1	B	2.56	631	1.31	1,156
259	Int’l-061	Bimbo, Central African	1	A	2.62	648	1.35	1,187
260	Int’l-062	Moundou, Chad	1	A	2.76	681	1.41	1,248
261	Int’l-085	Moroni, Comoros	2	A	2.52	588	1.21	1,057
262	Int’l-086	Kinshasa, Congo, Dem. Rep.	1	A	2.52	85	0.15	158
263	Int’l-087	Brazzaville, Congo, Rep.	1	A	2.52	85	0.15	158
264	Int’l-089	Abidjan, Cote d'Ivoire	1	A	2.58	484	0.84	767
265	Int’l-094	Djibouti, Djibouti	1	B	2.89	717	1.49	1,317
266	Int’l-098	Faraskur, Egypt	2	B	2.58	515	0.94	826
267	Int’l-100	Bata, Equatorial Guinea	1	A	2.55	548	1.02	919
268	Int’l-101	Asmara, Eritrea	3	A	2.47	552	1.13	974
269	Int’l-103	Dessie, Ethiopia	3	C	2.46	536	1.09	935
270	Int’l-116	Port-Gentil, Gabon	1	A	2.37	525	1.00	892
271	Int’l-125	Madina, Ghana	1	A	2.62	649	1.35	1,192
272	Int’l-132	Coyah, Guinea	1	A	2.60	184	0.38	358
273	Int’l-133	Bissau, Guinea-Bissau	1	A	2.67	662	1.38	1,215
274	Int’l-172	Kakamega, Kenya	1	A	2.72	212	0.45	488
275	Int’l-179	Maseru, Lesotho	3	C	3.04	78	0.12	65
276	Int’l-180	Monrovia, Liberia	1	A	2.56	635	1.32	1,166
277	Int’l-181	Al Jadidah, Libya	2	B	2.54	544	1.05	921
278	Int’l-186	Mahajanga, Madagascar	1	A	2.61	746	1.68	2,101
279	Int’l-187	Lilonge, Malawi	3	A	2.47	663	1.48	1,827
280	Int’l-190	Mopti, Mali	1	B	2.86	703	1.46	1,286
281	Int’l-192	Nouakchott, Mauritania	1	B	2.61	635	1.32	1,158
282	Int’l-193	Port Louis, Mauritius	1	A	2.63	653	1.48	1,880
283	Int’l-202	Mohammedia, Morocco	3	B	2.45	663	1.48	1,942
284	Int’l-203	Tete, Mozambique	1	B	2.67	15	0.03	45
285	Int’l-205	indhoek, Namibia	3	B	2.20	752	1.80	2,682
286	Int’l-213	Alaghsas, Niger	1	B	2.90	839	1.89	2,370
287	Int’l-214	Makurdi, Nigeria	1	A	2.74	574	1.04	933
288	Int’l-227	Le Tampon, French Reunion	1	A	2.62	310	0.65	624
289	Int’l-239	Gisenyi, Rwanda	1	A	2.57	156	0.32	305
290	Int’l-240	Jameston, British Territory	2	B	2.45	574	1.18	1,032
291	Int’l-243	São Tomé	1	A	2.53	395	0.82	737
292	Int’l-247	Kolda, Senegal	1	A	2.78	684	1.42	1,251
293	Int’l-249	Victoria, Seychelles	1	A	2.70	670	1.39	1,230
294	Int’l-250	Bo, Sierra Leone	1	A	2.56	229	0.48	439
295	Int’l-255	Hargeysa, Somalia	1	B	2.82	701	1.46	1,288
296	Int’l-256	Stellenbosch, South Africa	3	C	2.48	47	0.10	3,887
297	Int’l-257	Bloemfontein, South Africa	3	C	3.01	813	1.89	2,694
298	Int’l-258	Cape Town, South Africa	3	A	2.39	42	0.10	3,835
299	Int’l-267	Mbabane, Swaziland	3	A	2.46	104	0.21	260
300	Int’l-272	Songea, Tanzania	2	A	2.46	35	0.06	70

Table 8. (continued)

Figures Rfe. ID	Project ID	Locations Info	ASHREA Climate Zone		Annual Energy kBtu (millions)	Greenhouse Gases Eq CO_2 (Metric Tons)	Human Health (DALY)	Water Depletion (m3)
301	Int'l-274	Lome, Togo	1	A	2.67	664	1.38	1,219
302	Int'l-277	Monastir, Tunisia	2	B	2.46	473	0.84	733
303	Int'l-282	Arua, Uganda	1	A	2.57	231	0.48	437
304	Int'l-297	El Aaiún, Wstern Sahara	2	B	2.49	584	1.21	1,051
305	Int'l-299	Mufulira, Zambia	2	A	2.52	581	1.19	1,037
306	Int'l-300	Eporth, Zimbabe	3	A	2.48	759	1.79	2,615
307	Int'l-022	Riffa, Bahrain	1	B	2.84	563	0.98	880
308	Int'l-152	Najaf, Iraq	1	B	3.15	712	1.46	1,262
309	Int'l-154	Tel Aviv, Israel	2	A	2.53	693	1.54	2,072
310	Int'l-174	Kuwait City, Kuwait	1	B	2.77	622	1.23	1,082
311	Int'l-178	Beirut, Lebanon	2	A	2.61	581	1.19	1,028
312	Int'l-217	Salalah, Oman	1	B	2.61	549	1.00	896
313	Int'l-226	Al-Rayyan, Qatar	1	B	2.90	575	1.00	898
314	Int'l-244	Az Zulfi, Saudi Arabia	1	B	2.85	618	1.20	1,052
315	Int'l-245	Al Jubayl, Saudi Arabia	1	B	2.88	636	1.23	1,090
316	Int'l-246	Şabyā, Saudi Arabia	1	B	2.91	664	1.29	1,152
317	Int'l-284	Ajman, United Arab Emirates	1	B	2.89	582	1.02	918
318	Int'l-298	Al Mukalla, Yemen	1	B	2.78	687	1.43	1,259
319	Int'l-001	Maymana, Afghanistan	3	B	3.19	541	0.93	777
320	Int'l-023	Sandip, Bangladesh	1	A	3.13	387	0.67	543
321	Int'l-029	Thimphu, Bhutan	6	A	3.10	110	0.17	74
322	Int'l-139	Narasapur, India	1	A	2.68	855	1.99	2,861
323	Int'l-140	Manjeri, India	1	A	2.67	161	0.37	565
324	Int'l-141	Nawalgarh, India	1	B	2.79	730	1.69	2,447
325	Int'l-142	Madhupur, India	1	A	2.62	813	1.89	2,698
326	Int'l-143	Fatehpur, India	1	A	2.74	849	1.97	2,811
327	Int'l-144	Tirupati, India	1	A	2.69	42	0.11	359
328	Int'l-145	Bhiani, India	1	B	2.81	864	2.00	2,859
329	Int'l-146	Chikhli, India	1	A	2.70	775	1.80	2,579
330	Int'l-147	Karwar, India	1	B	2.79	37	0.09	2,191
331	Int'l-148	Miryalaguda, India	1	B	2.75	715	1.66	2,393
332	Int'l-189	Malé, Maldives	1	A	2.72	676	1.41	1,242
333	Int'l-206	Birgunj, Nepal	1	A	2.76	370	0.76	679
334	Int'l-218	Shahdadkot, Pakistan	1	B	2.96	658	1.28	1,132
335	Int'l-265	Galle, Sri Lanka	1	A	2.69	165	0.34	327
336	Int'l-012	Perth, Australia	2	A	2.48	714	1.64	2,333
337	Int'l-013	Darwin, Australia	1	A	2.71	857	2.00	2,892
338	Int'l-014	Gold Coast, Australia	2	A	2.47	675	1.56	2,228
339	Int'l-015	Albury, Australia	3	C	3.07	81	0.12	67
340	Int'l-016	Geelong est, Australia	3	C	2.83	631	1.41	1,928
341	Int'l-017	Rainbo Beach, Australia	2	A	2.49	734	1.70	2,446
342	Int'l-018	Tonsville, Australia	1	A	2.59	640	1.49	2,182
343	Int'l-044	Bandar Seri, Brunei Darussalam	1	A	2.75	534	0.93	848
344	Int'l-048	Ta Khmau, Cambodia	1	A	2.71	587	1.22	1,082
345	Int'l-064	Heze, China	3	A	3.15	836	1.93	2,747
346	Int'l-065	Changji, China	5	B	3.69	837	1.90	2,618
347	Int'l-066	Chaoyang, China	6	A	4.07	528	1.12	1,394
348	Int'l-067	Jixi, China	7	-	4.35	748	1.62	2,092
349	Int'l-068	Hailar, China	7	-	4.94	919	1.99	2,548
350	Int'l-069	Dandong, China	5	A	3.49	321	0.67	803

Table 8. (continued)

Figures Rfe. ID	Project ID	Locations Info	ASHREA Climate Zone		Annual Energy kBtu (millions)	Greenhouse Gases Eq CO_2 (Metric Tons)	Human Health (DALY)	Water Depletion (m3)
351	Int’l-070	Jinchang, China	5	B	3.56	805	1.82	2,489
352	Int’l-071	Chengdu, China	3	A	2.81	124	0.25	309
353	Int’l-072	Hotan, China	3	B	3.35	861	1.98	2,797
354	Int’l-073	Rikaze, China	5	A	3.32	116	0.18	78
355	Int’l-074	Dasha, China	2	A	2.52	736	1.75	2,582
356	Int’l-075	Benxi, China	6	A	3.79	847	1.90	2,591
357	Int’l-076	Renqiu, China	2	A	3.36	837	1.92	2,704
358	Int’l-077	Lengshuijiang, China	2	A	2.60	281	0.64	888
359	Int’l-078	enshang, China	3	A	3.23	816	1.88	2,655
360	Int’l-079	Yucheng, China	3	A	3.29	847	1.95	2,754
361	Int’l-080	Acheng, China	7	-	4.28	878	1.94	2,581
362	Int’l-081	Yutanzhen, China	3	A	2.99	804	1.87	2,676
363	Int’l-082	Jinzhou, China	5	A	3.64	844	1.91	2,637
364	Int’l-083	Licheng, China	3	A	2.99	818	1.90	2,722
365	Int’l-105	Lautoka, Fiji	3	A	2.33	90	0.17	154
366	Int’l-115	Papeete, French Polynesia	3	A	2.33	337	0.68	589
367	Int’l-130	Hagåtña, US Territory	1	A	2.47	599	1.24	1,090
368	Int’l-149	Pandeglang Regency, Indonesia	1	A	2.60	710	1.57	2,009
369	Int’l-150	Ciamis Regency, Indonesia	1	A	2.56	213	0.47	612
370	Int’l-151	Banjar, Indonesia	2	A	2.37	603	1.32	1,671
371	Int’l-163	Tokuyama, Japan	3	C	2.86	442	0.92	2,286
372	Int’l-164	Itoman, Japan	1	A	2.47	604	1.29	1,618
373	Int’l-165	Hiratsuka, Japan	3	C	2.85	598	1.24	1,472
374	Int’l-166	Ho • fu, Japan	3	A	2.50	407	0.86	2,207
375	Int’l-167	Ōita, Japan	3	C	2.85	361	0.75	2,535
376	Int’l-168	Fukushima-shi, Japan	4	A	3.15	252	0.50	3,095
377	Int’l-169	Chikusei, Japan	4	A	2.94	579	1.20	1,560
378	Int’l-170	Amman, Jordan	3	B	2.55	474	0.84	726
379	Int’l-173	Taraa, Kiribati	1	A	2.45	605	1.26	1,109
380	Int’l-176	Savannakhet, Laos	1	A	2.61	10	0.02	43
381	Int’l-184	Macau, Macau (China)	2	A	2.48	713	1.61	2,242
382	Int’l-188	Muar, Malaysia	1	A	2.73	684	1.40	1,706
383	Int’l-200	Erdenet, Mongolia	7	-	4.75	882	1.91	2,427
384	Int’l-204	Pyinmana, Myanmar	1	A	2.64	12	0.02	44
385	Int’l-210	Nouméa, New Caledonia	2	A	2.43	673	1.52	1,902
386	Int’l-211	Tauranga, New Zealand	3	C	2.33	186	0.36	412
387	Int’l-215	Alofi, Niue	3	A	2.33	521	1.07	918
388	Int’l-220	Port Moresby, New Guinea	1	A	2.49	229	0.44	409
389	Int’l-223	Lapu-Lapu City, Philippines	1	A	2.67	334	0.72	1,023
390	Int’l-242	Apia, Samoa	3	A	2.33	349	0.71	611
391	Int’l-251	Singapore, Singapore	1	A	2.74	578	1.05	946
392	Int’l-254	Honiara, Solomon Islands	1	A	2.44	603	1.25	1,106
393	Int’l-259	Keizan, South Korea	4	A	3.13	258	0.54	3,533
394	Int’l-260	Osan, South Korea	4	A	3.27	719	1.56	2,021
395	Int’l-261	Andong, South Korea	4	A	3.26	102	0.19	4,045
396	Int’l-270	Daxi, Taiwan	2	A	2.42	352	0.80	3,155
397	Int’l-273	Phetchabun, Thailand	2	A	2.60	26	0.07	215
398	Int’l-275	Nuku‘alofa, Tonga	3	A	2.33	520	1.07	917
399	Int’l-294	Port-Vila, Vanuatu	1	A	2.43	593	1.23	1,082
400	Int’l-296	Hải Dương , Vietnam	1	A	2.55	604	1.21	1,420

Table 9. International Sites - Electric Power Plant Sources Details

ID	Locations Info	Fossil	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Int’l-001	Maymana, Afghanistan	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Int’l-002	Shkodër, Albania	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-003	Bougara, Algeria	100.00%	0.00%	2.00%	98.00%	0.00%	0.00%	0.00%	0.00%
Int’l-004	Lubango, Angola	55.95%	0.00%	55.95%	0.00%	0.00%	44.05%	0.00%	0.00%
Int’l-005	St. John's, Antigua & Barbuda	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-006	Venado Tuerto, Argentina	100.00%	5.00%	17.00%	78.00%	0.00%	0.00%	0.00%	0.00%
Int’l-007	Concordia , Argentina	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-008	Puerto Madryn, Argentina	100.00%	5.00%	17.00%	78.00%	0.00%	0.00%	0.00%	0.00%
Int’l-009	Rosario, Argentina	100.00%	5.00%	17.00%	78.00%	0.00%	0.00%	0.00%	0.00%
Int’l-010	Resistencia, Argentina	100.00%	5.00%	17.00%	78.00%	0.00%	0.00%	0.00%	0.00%
Int’l-011	Gyumri, Armenia	22.74%	22.74%	0.00%	0.00%	48.52%	28.74%	0.00%	0.00%
Int’l-012	Perth, Australia	98.96%	83.13%	0.99%	14.84%	0.00%	0.00%	1.04%	0.00%
Int’l-013	Darwin, Australia	98.14%	82.44%	0.98%	14.72%	0.00%	0.00%	1.86%	0.00%
Int’l-014	Gold Coast, Australia	90.79%	76.26%	0.91%	13.62%	0.00%	5.33%	3.88%	0.00%
Int’l-015	Albury, Australia	0.08%	0.00%	0.08%	0.00%	0.00%	99.92%	0.00%	0.00%
Int’l-016	Geelong est, Australia	90.46%	75.99%	0.90%	13.57%	0.00%	1.45%	8.09%	0.00%
Int’l-017	Rainbo Beach, Australia	96.22%	80.82%	0.97%	14.43%	0.00%	0.08%	3.70%	0.00%
Int’l-018	Tonsville, Australia	77.88%	65.42%	0.78%	11.68%	0.00%	0.00%	22.12%	0.00%
Int’l-019	Innsbruck, Austria	25.82%	6.97%	1.29%	17.56%	0.00%	71.47%	2.71%	0.00%
Int’l-020	Baku, Azerbaijan	100.00%	0.00%	3.00%	97.00%	0.00%	0.00%	0.00%	0.00%
Int’l-021	Nassau, Bahamas	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-022	Riffa, Bahrain	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Int’l-023	Sandip, Bangladesh	71.22%	1.43%	3.56%	66.23%	0.00%	28.78%	0.00%	0.00%
Int’l-024	Polatsk, Belarus	99.98%	0.00%	18.00%	81.98%	0.00%	0.02%	0.00%	0.00%
Int’l-025	Liege, Belgium	64.06%	10.89%	0.00%	53.17%	32.41%	0.51%	3.02%	0.00%
Int’l-026	Belize City, Belize	53.47%	0.00%	53.47%	0.00%	0.00%	0.00%	46.53%	0.00%
Int’l-027	Cotonou, Benin	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-028	Hamilton, British Overseas Ter.	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-029	Thimphu, Bhutan	0.09%	0.00%	0.00%	0.09%	0.00%	99.91%	0.00%	0.00%
Int’l-030	Potosí, Bolivia	71.24%	0.00%	2.14%	69.10%	0.00%	28.76%	0.00%	0.00%
Int’l-031	Bihać, Bosnia & Herzegovina	31.72%	31.72%	0.00%	0.00%	0.00%	67.07%	1.21%	0.00%
Int’l-032	Selebi-Phike, Botsana	100.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-033	Manaus, Brazil	100.00%	29.00%	33.00%	38.00%	0.00%	0.00%	0.00%	0.00%
Int’l-034	Salvador, Brazil	27.35%	7.93%	9.03%	10.39%	0.00%	72.65%	0.00%	0.00%
Int’l-035	Cabo, Brazil	76.39%	22.15%	25.21%	29.03%	0.00%	0.46%	23.15%	0.00%
Int’l-036	Sobral, Brazil	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-037	Barreiras, Brazil	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-038	Botucatu, Brazil	0.00%	0.00%	0.00%	0.00%	0.00%	55.96%	44.04%	0.00%
Int’l-039	Abaetetuba, Brazil	100.00%	29.00%	33.00%	38.00%	0.00%	0.00%	0.00%	0.00%
Int’l-040	Taboão da Serra, Brazil	13.42%	3.89%	4.43%	5.10%	0.00%	82.47%	4.11%	0.00%
Int’l-041	TrÃªs Lagoas, Brazil	0.30%	0.00%	0.00%	0.30%	0.00%	96.57%	3.13%	0.00%
Int’l-042	Ouro Preto, Brazil	19.64%	5.70%	6.48%	7.46%	0.00%	51.22%	29.14%	0.00%
Int’l-043	Road Ton, British Virgin Islands	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-044	Bandar Seri, Brunei Darussalam	95.45%	0.00%	0.95%	94.50%	0.00%	4.55%	0.00%	0.00%
Int’l-045	Ardino, Bulgaria	90.77%	81.69%	0.00%	9.08%	0.00%	7.68%	1.55%	0.00%
Int’l-046	Bobo-Dioulasso, Burkina Faso	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-047	Bujumbura, Burundi	3.34%	0.00%	3.34%	0.00%	0.00%	96.66%	0.00%	0.00%
Int’l-048	Ta Khmau, Cambodia	87.09%	0.00%	87.09%	0.00%	0.00%	12.91%	0.00%	0.00%
Int’l-049	Mbouda, Cameroon	99.89%	0.00%	75.92%	23.97%	0.00%	0.11%	0.00%	0.00%
Int’l-050	Waterloo, Canada	91.44%	61.26%	6.40%	23.77%	0.00%	1.62%	6.94%	0.00%

Table 9. (continued)

ID	Locations Info	Fossil	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Int’l-051	Halifax, Canada	69.92%	46.85%	4.89%	18.18%	0.00%	29.36%	0.72%	0.00%
Int’l-052	Dartmouth, Canada	69.73%	46.72%	4.88%	18.13%	0.00%	29.27%	1.00%	0.00%
Int’l-053	Lethbridge, Canada	6.37%	4.27%	0.45%	1.66%	0.00%	36.88%	56.75%	0.00%
Int’l-054	Terrebonne, Canada	1.71%	1.15%	0.12%	0.44%	0.00%	94.32%	3.97%	0.00%
Int’l-055	Langley, Canada	32.31%	21.65%	2.26%	8.40%	0.00%	59.08%	8.61%	0.00%
Int’l-056	Fort McMurray, Canada	100.00%	67.00%	7.00%	26.00%	0.00%	0.00%	0.00%	0.00%
Int’l-057	St. John's, Canada	2.53%	1.70%	0.18%	0.66%	0.00%	97.25%	0.22%	0.00%
Int’l-058	Saguenay, Canada	0.18%	0.12%	0.01%	0.05%	0.00%	97.38%	2.44%	0.00%
Int’l-059	Prince George, Canada	0.00%	0.00%	0.00%	0.00%	0.00%	0.35%	99.65%	0.00%
Int’l-060	Praia, Cape Verde	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-061	Bimbo, Central African	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-062	Moundou, Chad	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-063	Coquimbo, Chile	0.00%	0.00%	0.00%	0.00%	0.00%	86.22%	13.78%	0.00%
Int’l-064	Heze, China	100.00%	99.00%	1.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-065	Changji, China	95.86%	94.90%	0.96%	0.00%	0.00%	0.00%	4.14%	0.00%
Int’l-066	Chaoyang, China	51.81%	51.29%	0.52%	0.00%	0.00%	47.90%	0.29%	0.00%
Int’l-067	Jixi, China	81.08%	80.27%	0.81%	0.00%	0.00%	18.92%	0.00%	0.00%
Int’l-068	Hailar, China	100.00%	99.00%	1.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-069	Dandong, China	29.03%	28.74%	0.29%	0.00%	0.00%	70.97%	0.00%	0.00%
Int’l-070	Jinchang, China	98.62%	97.63%	0.99%	0.00%	0.00%	1.22%	0.16%	0.00%
Int’l-071	Chengdu, China	9.46%	9.37%	0.09%	0.00%	0.00%	90.54%	0.00%	0.00%
Int’l-072	Hotan, China	100.00%	99.00%	1.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-073	Rikaze, China	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-074	Dasha, China	88.89%	88.00%	0.89%	0.00%	0.00%	10.98%	0.13%	0.00%
Int’l-075	Benxi, China	100.00%	99.00%	1.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-076	Renqiu, China	97.23%	96.26%	0.97%	0.00%	0.00%	2.77%	0.00%	0.00%
Int’l-077	Lengshuijiang, China	32.78%	32.45%	0.33%	0.00%	0.00%	67.22%	0.00%	0.00%
Int’l-078	enshang, China	96.89%	95.92%	0.97%	0.00%	0.00%	3.03%	0.08%	0.00%
Int’l-079	Yucheng, China	100.00%	99.00%	1.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-080	Acheng, China	99.58%	98.58%	1.00%	0.00%	0.00%	0.40%	0.02%	0.00%
Int’l-081	Yutanzhen, China	97.14%	96.17%	0.97%	0.00%	0.00%	2.86%	0.00%	0.00%
Int’l-082	Jinzhou, China	98.89%	97.90%	0.99%	0.00%	0.00%	0.76%	0.35%	0.00%
Int’l-083	Licheng, China	99.21%	98.22%	0.99%	0.00%	0.00%	0.76%	0.03%	0.00%
Int’l-084	Sabanalarga, Colombia	100.00%	27.00%	2.00%	71.00%	0.00%	0.00%	0.00%	0.00%
Int’l-085	Moroni, Comoros	99.82%	0.00%	99.82%	0.00%	0.00%	0.18%	0.00%	0.00%
Int’l-086	Kinshasa, Congo, Dem. Rep.	15.32%	0.00%	0.00%	15.32%	0.00%	84.68%	0.00%	0.00%
Int’l-087	Brazzaville, Congo, Rep.	15.32%	0.00%	0.00%	15.32%	0.00%	84.68%	0.00%	0.00%
Int’l-088	San Jose, Costa Rica	2.57%	0.00%	2.57%	0.00%	0.00%	96.53%	0.90%	0.00%
Int’l-089	Abidjan, Cote d'Ivoire	92.66%	0.00%	0.00%	92.66%	0.00%	7.34%	0.00%	0.00%
Int’l-090	Split, Croatia	2.19%	0.00%	0.00%	2.19%	0.00%	97.81%	0.00%	0.00%
Int’l-091	Larnaca, Cyprus	99.94%	0.00%	99.94%	0.00%	0.00%	0.00%	0.06%	0.00%
Int’l-092	Zlín, Czech Republic	44.54%	44.09%	0.00%	0.45%	42.56%	12.16%	0.74%	0.00%
Int’l-093	Aalborg, Denmark	62.04%	42.81%	3.10%	16.13%	0.00%	0.28%	37.68%	0.00%
Int’l-094	Djibouti, Djibouti	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-095	Roseau, Dominica	99.46%	0.00%	99.46%	0.00%	0.00%	0.54%	0.00%	0.00%
Int’l-096	San Francisco, Dominican Rep.	64.36%	9.01%	45.70%	9.65%	0.00%	35.64%	0.00%	0.00%
Int’l-097	Babahoyo, Ecuador	84.12%	0.00%	71.50%	12.62%	0.00%	15.88%	0.00%	0.00%
Int’l-098	Faraskur, Egypt	100.00%	0.00%	24.00%	76.00%	0.00%	0.00%	0.00%	0.00%
Int’l-099	San Marcos, El Salvador	49.63%	0.00%	49.63%	0.00%	0.00%	11.01%	39.36%	0.00%
Int’l-100	Bata, Equatorial Guinea	98.43%	0.00%	32.48%	65.95%	0.00%	1.57%	0.00%	0.00%

Table 9. (continued)

ID	Locations Info	Fossil	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Int'l-101	Asmara, Eritrea	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int'l-102	Tartu, Estonia	1.86%	0.00%	0.78%	1.08%	0.00%	2.94%	95.20%	0.00%
Int'l-103	Dessie, Ethiopia	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int'l-104	Stanley, British Territory	89.55%	0.00%	89.55%	0.00%	0.00%	0.00%	10.45%	0.00%
Int'l-105	Lautoka, Fiji	11.85%	0.00%	11.85%	0.00%	0.00%	85.39%	2.76%	0.00%
Int'l-106	Vantaa, Finland	58.28%	33.22%	0.58%	24.48%	38.81%	1.99%	0.92%	0.00%
Int'l-107	Ajaccio, France	65.55%	32.78%	6.56%	26.22%	0.00%	28.22%	6.23%	0.00%
Int'l-108	Nice, France	7.24%	3.62%	0.72%	2.90%	0.00%	92.31%	0.45%	0.00%
Int'l-109	Aix-en-Provence, France	46.82%	23.41%	4.68%	18.73%	0.00%	51.44%	1.74%	0.00%
Int'l-110	Saint-Denis, France	28.15%	14.08%	2.82%	11.26%	66.56%	0.21%	5.08%	0.00%
Int'l-111	Villeurbanne, France	4.18%	2.09%	0.42%	1.67%	77.93%	17.75%	0.14%	0.00%
Int'l-112	Pau, France	3.40%	1.70%	0.34%	1.36%	0.00%	95.10%	1.50%	0.00%
Int'l-113	Châteauroux, France	1.72%	0.86%	0.17%	0.69%	94.72%	2.94%	0.62%	0.00%
Int'l-114	Cayenne, French Guiana	97.56%	0.00%	97.56%	0.00%	0.00%	0.00%	2.44%	0.00%
Int'l-115	Papeete, French Polynesia	62.36%	0.00%	62.36%	0.00%	0.00%	37.64%	0.00%	0.00%
Int'l-116	Port-Gentil, Gabon	100.00%	0.00%	42.00%	58.00%	0.00%	0.00%	0.00%	0.00%
Int'l-117	Kutaisi, Georgia	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int'l-118	Freiburg, Germany	6.87%	5.15%	0.14%	1.58%	75.97%	15.17%	1.99%	0.00%
Int'l-119	Eimsbüttel, Germany	40.22%	30.17%	0.80%	9.25%	40.42%	0.69%	18.67%	0.00%
Int'l-120	Düsseldorf, Germany	95.95%	71.96%	1.92%	22.07%	0.00%	0.93%	3.12%	0.00%
Int'l-121	Rosenheim, Germany	27.24%	20.43%	0.54%	6.27%	49.76%	20.73%	2.27%	0.00%
Int'l-122	Görlitz, Germany	97.50%	73.13%	1.95%	22.43%	0.00%	0.55%	1.95%	0.00%
Int'l-123	Heidenheim an der Bre., Germany	19.68%	14.76%	0.39%	4.53%	73.35%	3.83%	3.14%	0.00%
Int'l-124	Stralsund, Germany	65.55%	49.16%	1.31%	15.08%	0.00%	0.04%	34.41%	0.00%
Int'l-125	Madina, Ghana	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int'l-126	Gibraltar, British Overseas Ter.	87.72%	0.00%	87.72%	0.00%	0.00%	0.69%	11.59%	0.00%
Int'l-127	Thessaloniki, Greece	92.09%	59.86%	13.81%	18.42%	0.00%	7.29%	0.62%	0.00%
Int'l-128	Nuuk, Greenland	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int'l-129	Saint George's, Grenada	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int'l-130	Hagåtña, US Territory	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int'l-131	Guatemala City, Guatemala	39.40%	7.49%	31.91%	0.00%	0.00%	24.74%	35.86%	0.00%
Int'l-132	Coyah, Guinea	27.68%	0.00%	27.68%	0.00%	0.00%	72.32%	0.00%	0.00%
Int'l-133	Bissau, Guinea-Bissau	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int'l-134	Georgeton, Guyana	96.66%	0.00%	96.66%	0.00%	0.00%	0.00%	3.34%	0.00%
Int'l-135	Gonaïves, Haiti	91.94%	0.00%	91.94%	0.00%	0.00%	8.06%	0.00%	0.00%
Int'l-136	Tegucigalpa, Honduras	98.29%	0.00%	98.29%	0.00%	0.00%	0.02%	1.69%	0.00%
Int'l-137	Székesfehérvár , Hungary	37.62%	13.54%	1.50%	22.57%	61.14%	0.00%	1.24%	0.00%
Int'l-138	Reykjavik, Iceland	0.00%	0.00%	0.00%	0.00%	0.00%	71.33%	28.67%	0.00%
Int'l-139	Narasapur, India	99.48%	81.57%	2.98%	14.92%	0.00%	0.33%	0.19%	0.00%
Int'l-140	Manjeri, India	17.82%	14.61%	0.53%	2.67%	0.00%	76.50%	5.68%	0.00%
Int'l-141	Nawalgarh, India	83.80%	68.72%	2.51%	12.57%	0.00%	0.00%	16.20%	0.00%
Int'l-142	Madhupur, India	99.32%	81.44%	2.98%	14.90%	0.00%	0.65%	0.03%	0.00%
Int'l-143	Fatehpur, India	100.00%	82.00%	3.00%	15.00%	0.00%	0.00%	0.00%	0.00%
Int'l-144	Tirupati, India	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%
Int'l-145	Bhiani, India	99.56%	81.64%	2.99%	14.93%	0.00%	0.26%	0.18%	0.00%
Int'l-146	Chikhli, India	90.74%	74.41%	2.72%	13.61%	0.00%	9.26%	0.00%	0.00%
Int'l-147	Karwar, India	1.92%	1.57%	0.06%	0.29%	40.41%	57.67%	0.00%	0.00%
Int'l-148	Miryalaguda, India	81.20%	66.58%	2.44%	12.18%	0.00%	18.26%	0.54%	0.00%
Int'l-149	Pandeglang Regency, Indonesia	96.53%	47.30%	25.10%	24.13%	0.00%	0.00%	3.47%	0.00%
Int'l-150	Ciamis Regency, Indonesia	28.65%	14.04%	7.45%	7.16%	0.00%	71.35%	0.00%	0.00%

Table 9. (continued)

ID	Locations Info	Fossil	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Int’l-151	Banjar, Indonesia	94.84%	46.47%	24.66%	23.71%	0.00%	5.16%	0.00%	0.00%
Int’l-152	Najaf, Iraq	99.79%	0.00%	99.79%	0.00%	0.00%	0.21%	0.00%	0.00%
Int’l-153	Tallaght, Ireland	87.41%	24.47%	3.50%	59.44%	0.00%	4.24%	8.35%	0.00%
Int’l-154	Tel Aviv, Israel	100.00%	63.00%	4.00%	33.00%	0.00%	0.00%	0.00%	0.00%
Int’l-155	Bagheria, Italy	76.35%	15.27%	9.16%	51.92%	0.00%	5.69%	17.96%	0.00%
Int’l-156	Siracusa, Italy	81.81%	16.36%	9.82%	55.63%	0.00%	14.66%	3.53%	0.00%
Int’l-157	Caserta, Italy	63.24%	12.65%	7.59%	43.00%	0.00%	18.59%	18.17%	0.00%
Int’l-158	Perugia, Italy	61.36%	12.27%	7.36%	41.72%	0.00%	20.94%	17.70%	0.00%
Int’l-159	Naples, Italy	59.42%	11.88%	7.13%	40.41%	0.00%	21.98%	18.60%	0.00%
Int’l-160	Marsala, Italy	36.29%	7.26%	4.35%	24.68%	0.00%	25.09%	38.62%	0.00%
Int’l-161	Catanzaro, Italy	86.36%	17.27%	10.36%	58.72%	0.00%	10.28%	3.36%	0.00%
Int’l-162	Spanish Ton, Jamaica	92.72%	0.00%	92.72%	0.00%	0.00%	4.72%	2.56%	0.00%
Int’l-163	Tokuyama, Japan	67.56%	29.05%	9.46%	29.05%	30.05%	2.21%	0.18%	0.00%
Int’l-164	Itoman, Japan	93.16%	40.06%	13.04%	40.06%	0.00%	6.66%	0.18%	0.00%
Int’l-165	Hiratsuka, Japan	97.92%	42.11%	13.71%	42.11%	0.00%	1.31%	0.77%	0.00%
Int’l-166	Ho⍰fu, Japan	67.78%	29.15%	9.49%	29.15%	30.39%	1.55%	0.28%	0.00%
Int’l-167	Ōita, Japan	53.02%	22.80%	7.42%	22.80%	41.65%	4.94%	0.39%	0.00%
Int’l-168	Fukushima-shi, Japan	28.98%	12.46%	4.06%	12.46%	66.67%	3.89%	0.46%	0.00%
Int’l-169	Chikusei, Japan	92.07%	39.59%	12.89%	39.59%	3.76%	3.23%	0.94%	0.00%
Int’l-170	Amman, Jordan	99.57%	0.00%	10.95%	88.62%	0.00%	0.28%	0.15%	0.00%
Int’l-171	Kentau, Kazakhstan	100.00%	82.00%	4.00%	14.00%	0.00%	0.00%	0.00%	0.00%
Int’l-172	Kakamega, Kenya	29.23%	0.00%	29.23%	0.00%	0.00%	41.24%	29.53%	0.00%
Int’l-173	Taraa, Kiribati	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-174	Kuwait City, Kuwait	100.00%	0.00%	71.00%	29.00%	0.00%	0.00%	0.00%	0.00%
Int’l-175	Osh, Kyrgyz Republic	15.34%	3.68%	0.00%	11.66%	0.00%	84.66%	0.00%	0.00%
Int’l-176	Savannakhet, Laos	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-177	Liepāja, Latvia	64.17%	0.00%	0.00%	64.17%	0.00%	0.00%	35.83%	0.00%
Int’l-178	Beirut, Lebanon	98.50%	0.00%	97.52%	0.99%	0.00%	1.50%	0.00%	0.00%
Int’l-179	Maseru, Lesotho	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-180	Monrovia, Liberia	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-181	Al Jadidah, Libya	100.00%	0.00%	59.00%	41.00%	0.00%	0.00%	0.00%	0.00%
Int’l-182	Alytus, Lithuania	80.54%	0.00%	21.75%	58.79%	0.00%	12.28%	7.18%	0.00%
Int’l-183	Luxembourg, Luxembourg	40.08%	0.00%	0.00%	40.08%	54.23%	1.87%	3.82%	0.00%
Int’l-184	Macau, Macau (China)	98.81%	70.16%	0.00%	28.65%	0.00%	1.04%	0.15%	0.00%
Int’l-185	Prilep, Macedonia	91.32%	87.67%	3.65%	0.00%	0.00%	8.68%	0.00%	0.00%
Int’l-186	Mahajanga, Madagascar	100.00%	50.00%	50.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-187	Lilonge, Malawi	100.00%	50.00%	50.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-188	Muar, Malaysia	100.00%	33.00%	2.00%	65.00%	0.00%	0.00%	0.00%	0.00%
Int’l-189	Malé, Maldives	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-190	Mopti, Mali	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-191	Valletta, Malta	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-192	Nouakchott, Mauritania	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-193	Port Louis, Mauritius	84.15%	42.08%	42.08%	0.00%	0.00%	5.26%	10.59%	0.00%
Int’l-194	Río Bravo, Mexico	99.92%	13.99%	20.98%	64.95%	0.00%	0.00%	0.08%	0.00%
Int’l-195	Cholula, Mexico	95.26%	13.34%	20.00%	61.92%	0.00%	4.74%	0.00%	0.00%
Int’l-196	Guadalupe, Mexico	99.50%	13.93%	20.90%	64.68%	0.00%	0.00%	0.50%	0.00%
Int’l-197	Colima, Mexico	90.66%	12.69%	19.04%	58.93%	0.00%	9.34%	0.00%	0.00%
Int’l-198	Juchitán de zaragoza, Mexico	30.54%	4.28%	6.41%	19.85%	0.00%	0.00%	69.46%	0.00%
Int’l-199	Tiraspol, Moldova	100.00%	0.00%	4.00%	96.00%	0.00%	0.00%	0.00%	0.00%
Int’l-200	Erdenet, Mongolia	100.00%	96.00%	4.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 9. (continued)

ID	Locations Info	Fossil	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Int’l-201	Podgorica, Montenegro	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-202	Mohammedia, Morocco	100.00%	61.00%	24.00%	15.00%	0.00%	0.00%	0.00%	0.00%
Int’l-203	Tete, Mozambique	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-204	Pyinmana, Myanmar	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-205	indhoek, Namibia	100.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-206	Birgunj, Nepal	54.78%	0.00%	54.78%	0.00%	0.00%	45.22%	0.00%	0.00%
Int’l-207	Nieuegein, Netherlands	61.64%	16.64%	1.23%	43.76%	29.90%	0.08%	8.38%	0.00%
Int’l-208	Dordrecht, Netherlands	70.17%	18.95%	1.40%	49.82%	23.40%	0.06%	6.37%	0.00%
Int’l-209	Bergen op Zoom, Netherlands	72.82%	19.66%	1.46%	51.70%	23.02%	0.06%	4.10%	0.00%
Int’l-210	Nouméa, New Caledonia	96.63%	48.32%	48.32%	0.00%	0.00%	0.01%	3.36%	0.00%
Int’l-211	Tauranga, New Zealand	31.37%	8.47%	0.00%	22.90%	0.00%	43.19%	25.44%	0.00%
Int’l-212	Masaya, Nicaragua	74.97%	0.00%	74.97%	0.00%	0.00%	0.16%	24.87%	0.00%
Int’l-213	Alaghsas, Niger	100.00%	50.00%	50.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-214	Makurdi, Nigeria	100.00%	0.00%	16.00%	84.00%	0.00%	0.00%	0.00%	0.00%
Int’l-215	Alofi, Niue	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-216	Oslo, Norway	0.00%	0.00%	0.00%	0.00%	0.00%	99.26%	0.74%	0.00%
Int’l-217	Salalah, Oman	100.00%	0.00%	18.00%	82.00%	0.00%	0.00%	0.00%	0.00%
Int’l-218	Shahdadkot, Pakistan	100.00%	0.00%	56.00%	44.00%	0.00%	0.00%	0.00%	0.00%
Int’l-219	Las Cumbres, Panama	71.83%	0.00%	71.83%	0.00%	0.00%	28.17%	0.00%	0.00%
Int’l-220	Port Moresby, Papua New Guinea	40.20%	0.00%	20.10%	20.10%	0.00%	59.80%	0.00%	0.00%
Int’l-221	Encarnación, Paraguay	33.40%	16.70%	16.70%	0.00%	0.00%	66.60%	0.00%	0.00%
Int’l-222	Juliaca, Peru	100.00%	7.00%	8.00%	85.00%	0.00%	0.00%	0.00%	0.00%
Int’l-223	Lapu-Lapu City, Philippines	44.31%	17.72%	5.32%	21.27%	0.00%	2.38%	53.31%	0.00%
Int’l-224	Mielec, Poland	98.44%	93.52%	1.97%	2.95%	0.00%	1.11%	0.45%	0.00%
Int’l-225	Odivelas, Portugal	84.06%	41.19%	7.57%	35.31%	0.00%	0.32%	15.62%	0.00%
Int’l-226	Al-Rayyan, Qatar	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Int’l-227	Le Tampon, French Reunion	46.56%	0.00%	46.56%	0.00%	0.00%	35.30%	18.14%	0.00%
Int’l-228	Targu Mures, Romania	45.76%	32.95%	1.37%	11.44%	0.00%	54.24%	0.00%	0.00%
Int’l-229	Pavlovo, Russia	100.00%	25.00%	3.00%	72.00%	0.00%	0.00%	0.00%	0.00%
Int’l-230	Berdsk, Russia	79.56%	19.89%	2.39%	57.28%	0.00%	20.44%	0.00%	0.00%
Int’l-231	Borisoglebsk, Russia	100.00%	25.00%	3.00%	72.00%	0.00%	0.00%	0.00%	0.00%
Int’l-232	Petropavlovsk-Kamchat., Russia	75.96%	18.99%	2.28%	54.69%	0.00%	0.00%	24.04%	0.00%
Int’l-233	Tuymazy, Russia	99.11%	24.78%	2.97%	71.36%	0.00%	0.89%	0.00%	0.00%
Int’l-234	Vladivostok, Russia	99.99%	25.00%	3.00%	71.99%	0.00%	0.00%	0.01%	0.00%
Int’l-235	Yakutsk, Russia	100.00%	25.00%	3.00%	72.00%	0.00%	0.00%	0.00%	0.00%
Int’l-236	Apatity, Russia	10.69%	2.67%	0.32%	7.70%	69.93%	19.38%	0.00%	0.00%
Int’l-237	Kogalym, Russia	100.00%	25.00%	3.00%	72.00%	0.00%	0.00%	0.00%	0.00%
Int’l-238	Novyy Urengoy, Russia	100.00%	25.00%	3.00%	72.00%	0.00%	0.00%	0.00%	0.00%
Int’l-239	Gisenyi, Rwanda	23.55%	0.00%	23.55%	0.00%	0.00%	76.40%	0.05%	0.00%
Int’l-240	Jameston, British overseas ter.	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-241	Saint-Pierre, Saint Pierre & Miq.	37.57%	0.00%	37.57%	0.00%	0.00%	31.16%	31.27%	0.00%
Int’l-242	Apia, Samoa	64.82%	0.00%	64.82%	0.00%	0.00%	35.12%	0.06%	0.00%
Int’l-243	São Tomé, São Tomé & Príncipe	62.47%	0.00%	62.47%	0.00%	0.00%	37.53%	0.00%	0.00%
Int’l-244	Az Zulfi, Saudi Arabia	100.00%	0.00%	56.00%	44.00%	0.00%	0.00%	0.00%	0.00%
Int’l-245	Al Jubayl, Saudi Arabia	100.00%	0.00%	56.00%	44.00%	0.00%	0.00%	0.00%	0.00%
Int’l-246	Şabyā, Saudi Arabia	100.00%	0.00%	56.00%	44.00%	0.00%	0.00%	0.00%	0.00%
Int’l-247	Kolda, Senegal	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-248	Vranje, Serbia	91.16%	91.16%	0.00%	0.00%	0.00%	8.84%	0.00%	0.00%
Int’l-249	Victoria, Seychelles	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-250	Bo, Sierra Leone	35.37%	0.00%	35.37%	0.00%	0.00%	64.63%	0.00%	0.00%

Table 9. (continued)

ID	Locations Info	Fossil	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Int’l-251	Singapore, Singapore	100.00%	0.00%	18.00%	82.00%	0.00%	0.00%	0.00%	0.00%
Int’l-252	Banská Bystrica, Slovak Republic	8.24%	5.11%	0.74%	2.39%	69.96%	21.70%	0.10%	0.00%
Int’l-253	Maribor, Slovenia	41.93%	37.74%	0.00%	4.19%	26.76%	29.22%	2.09%	0.00%
Int’l-254	Honiara, Solomon Islands	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-255	Hargeysa, Somalia	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-256	Stellenbosch, South Africa	0.01%	0.01%	0.00%	0.00%	98.55%	1.18%	0.26%	0.00%
Int’l-257	Bloemfontein, South Africa	100.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-258	Cape Town, South Africa	0.01%	0.01%	0.00%	0.00%	98.57%	1.16%	0.26%	0.00%
Int’l-259	Keizan, South Korea	26.65%	18.66%	1.87%	6.13%	71.84%	0.99%	0.52%	0.00%
Int’l-260	Osan, South Korea	99.09%	69.36%	6.94%	22.79%	0.00%	0.86%	0.05%	0.00%
Int’l-261	Andong, South Korea	0.00%	0.00%	0.00%	0.00%	97.99%	0.80%	1.21%	0.00%
Int’l-262	Algeciras, Spain	87.92%	20.22%	9.67%	58.03%	0.00%	0.50%	11.58%	0.00%
Int’l-263	Latina, Spain	70.82%	16.29%	7.79%	46.74%	0.00%	13.83%	15.35%	0.00%
Int’l-264	Jaén, Spain	17.71%	4.07%	1.95%	11.69%	0.00%	21.65%	60.64%	0.00%
Int’l-265	Galle, Sri Lanka	23.94%	0.00%	23.94%	0.00%	0.00%	76.06%	0.00%	0.00%
Int’l-266	Paramaribo, Suriname	42.72%	0.00%	42.72%	0.00%	0.00%	57.28%	0.00%	0.00%
Int’l-267	Mbabane, Swaziland	10.28%	5.14%	5.14%	0.00%	0.00%	73.56%	16.16%	0.00%
Int’l-268	Malmö, Sweden	82.58%	36.34%	14.04%	32.21%	0.00%	4.04%	13.38%	0.00%
Int’l-269	Basel, Switzerland	4.55%	0.00%	0.64%	3.91%	79.06%	14.56%	1.83%	0.00%
Int’l-270	Daxi, Taiwan	49.33%	34.53%	2.47%	12.33%	48.22%	1.25%	1.20%	0.00%
Int’l-271	Khujand, Tajikistan	9.27%	0.00%	0.00%	9.27%	0.00%	90.73%	0.00%	0.00%
Int’l-272	Songea, Tanzania	3.17%	0.22%	0.06%	2.88%	0.00%	96.83%	0.00%	0.00%
Int’l-273	Phetchabun, Thailand	0.00%	0.00%	0.00%	0.00%	0.00%	43.66%	56.34%	0.00%
Int’l-274	Lome, Togo	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-275	Nuku‘alofa, Tonga	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-276	Mon Repos, Trinidad & Tobago	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Int’l-277	Monastir, Tunisia	100.00%	0.00%	9.00%	91.00%	0.00%	0.00%	0.00%	0.00%
Int’l-278	Menemen, Turkey	98.69%	35.53%	2.96%	60.20%	0.00%	0.00%	1.31%	0.00%
Int’l-279	Tarsus, Turkey	93.04%	33.49%	2.79%	56.75%	0.00%	6.92%	0.04%	0.00%
Int’l-280	Söke, Turkey	94.34%	33.96%	2.83%	57.55%	0.00%	3.74%	1.92%	0.00%
Int’l-281	Ashgabat, Turkmenistan	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Int’l-282	Arua, Uganda	35.59%	0.00%	35.59%	0.00%	0.00%	64.41%	0.00%	0.00%
Int’l-283	Rivne, Ukraine	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
Int’l-284	Ajman, United Arab Emirates	100.00%	0.00%	2.00%	98.00%	0.00%	0.00%	0.00%	0.00%
Int’l-285	Portsmouth, United Kingdom	82.87%	32.32%	1.66%	48.89%	10.82%	0.00%	6.31%	0.00%
Int’l-286	Sindon, United Kingdom	84.08%	32.79%	1.68%	49.61%	9.45%	0.00%	6.47%	0.00%
Int’l-287	Corby, United Kingdom	95.72%	37.33%	1.91%	56.47%	0.00%	0.00%	4.28%	0.00%
Int’l-288	Horsham, United Kingdom	88.96%	34.69%	1.78%	52.49%	6.58%	0.00%	4.46%	0.00%
Int’l-289	Castlereagh, United Kingdom	89.33%	34.84%	1.79%	52.70%	0.00%	0.35%	10.32%	0.00%
Int’l-290	Clacton-on-Sea, United Kingdom	72.82%	28.40%	1.46%	42.96%	23.35%	0.00%	3.83%	0.00%
Int’l-291	Northampton, United Kingdom	94.06%	36.68%	1.88%	55.50%	0.00%	0.01%	5.93%	0.00%
Int’l-292	Salto, Uruguay	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Int’l-293	Kogon, Uzbekistan	100.00%	5.00%	2.00%	93.00%	0.00%	0.00%	0.00%	0.00%
Int’l-294	Port-Vila, Vanuatu	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-295	Alto Barinas, Venezuela	8.24%	0.00%	3.79%	4.45%	0.00%	91.76%	0.00%	0.00%
Int’l-296	Hải Dương , Vietnam	99.78%	27.94%	3.99%	67.85%	0.00%	0.22%	0.00%	0.00%
Int’l-297	El Aaiún, Wstern Sahara	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-298	Al Mukalla, Yemen	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-299	Mufulira, Zambia	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Int’l-300	Eporth, Zimbabe	100.00%	99.00%	1.00%	0.00%	0.00%	0.00%	0.00%	0.00%

APPENDIX B

SUPPLEMENTARY DATA FOR ON-SITE RENEWABLE ENERGY

This Appendix (B) shows the full data related to chapter 4. It comprises all simulation and modeling data for all sites (25) included in the study.

Figure 18. Distribution of the 25 locations within the study by power plant type/energy sources used

Table 10. Development of renewable energy requirements in different LEED versions

Version	Credit	Title	Requirements	Points	Points %[1]	Summary of changes and notes
LEED v2.0, 2001	EAc2.1 EAc2.2 EAc2.3	Renewable Energy	5% 10% 20%	1 2 3	18% of EA points	· Energy referenced standard start with ASHRAE 90.1-1999, the total EA points represent 25% of the total points in LEED v2.0 · Credit EAc2 first released as "Renewable Energy" with three possible points. · Credit EAc6 first released as "Green Power" with one possible point.
	EAc6	Green Power	0% for 2-Y Contract	1	6% of EA points	
LEED v2.1, 2003	EAc2.1 EAc2.2 EAc2.3	Renewable Energy	5% 10% 20%	1 2 3	18% of EA points	· Energy referenced standard remain as ASHRAE 90.1-1999, the total EA points represent 25% of the total points in LEED v2.1. · Overall no substantive changes, except for defining the required percentage for green power of 50%.
	EAc6	Green Power	50% for 2-Y Contract	1	6% of EA points	
LEED v2.2, 2005	EAc2.1 EAc2.2 EAc2.3	On-Site Renewable energy	2.5% 7.5% 12.5%	1 2 3	18% of EA points	· Energy referenced standard updated to ASHRAE 90.1-2004, the total EA points represent 25% of the total points in LEED v2.2 · Credit EAc2 title renamed from "Renewable Energy" · Credit Eac6, percentage reduced from 50% to 35%.
	EAc6	Green Power	35% for 2-Y Contract	1	6% of EA points	
LEED v3.0, 2009	EAc2.1 EAc2.2 EAc2.3 EAc2.4 EAc2.5 EAc2.6 EAc2.7	On-Site Renewable Energy	1% 3% 5% 7% 9% 11% 13%	1 2 3 4 5 6 7	20% of EA points	· Energy referenced standard updated to ASHRAE 90.1-2007, the total EA points represent 32% of the total points in LEED v3.0. · Credit EAc2 points reweighted from 1-3 points to 1-7 points, nevertheless the share of EA points remains slightly unchanged, because the entire EA section has been increased from 25% to 32%. Also, Lower and higher thresholds added · Credit EAc6, reweighted from 1 point to 2 points and purchases of green power are based on the quantity of energy consumed, not cost. Also, specify Green-e Energy products
	EAc6	Green Power	35% for 2-Y Contract	2	6% of EA points	
LEED v4.0, 2013	EAc5.1 EAc5.2 EAc5.3	Renewable Energy Production	1% 5% 10%	1 2 3	9% of EA points	· Energy referenced standard updated to ASHRAE 90.1-2010, the total EA points represent 30% of the total points in LEED v4.0 · Credit EAc2 title renamed from "On-Site Renewable Energy" and points adjusted significantly. Also, provision for community-scale renewable energy systems was added. EAc2.2 is not applicable to NC rating system. · Credit EAc6 title renamed from "Green Power". The required percentage has been increased. Credit based on total building energy usage. Carbon offsets allowed for scope 1 or 2 emissions. Required contract length extended from 2 years to 5 years. Eligible resources must have come online after January 1, 2005. · New pilot credit (1 point) titled "Renewable energy - distributed generation", to make the building structure capable of supporting planned photovoltaic technologies on the roof (Solar facility capacity: 250, 500 or 1,000 kW).
	EAc7.1 EAc7.2	Green Power and Carbon Offsets	50% for 5-Y Contract 100% for 5-Y Contract	1 2	6% of EA points	

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[1] Points %: represents the proportion of renewable energy or green power points out of the total points in the Energy and Atmosphere (EA) category.

Table 11. Electric power plant sources details in the 25 locations in the study site

ID[2]	Locations Info	Coal	Oil	Gas	Nuclear	Hydro	Renewable	Other
Nat'l- 098	Sodus, New York, United States	15%	1%	19%	31%	31%	4%	0%
Nat'l- 077	Honokaa, Hawaii, United States	2%	77%	0%	0%	2%	19%	0%
Nat'l-035	Farragut, Iowa, United States	69%	0%	2%	14%	4%	10%	0%
Nat'l-099	Phoenix, Arizona, United States	39%	0%	36%	17%	6%	3%	0%
Nat'l-075	Annapolis, California, United States	7%	1%	53%	15%	13%	10%	1%
Int'l-056	Fort McMurray, Alberta, Canada	67%	7%	26%	0%	0%	0%	0%
Int'l-106	Vantaa, Southern Finland, Finland	33%	1%	24%	39%	2%	1%	0%
Int'l-037	Barreiras, Bahia, Brazil	0%	0%	0%	0%	100%	0%	0%
Int'l-280	Söke, Aydın, Turkey	34%	3%	58%	0%	4%	2%	0%
Int'l-151	Banjar, Bali, Indonesia	46%	25%	24%	0%	5%	0%	0%
Int'l-214	Makurdi, Benue, Nigeria	0%	16%	84%	0%	0%	0%	0%
Int'l-289	Belfast, United Kingdom	35%	2%	53%	0%	0%	10%	0%
Int'l-192	Nouakchott, Mauritania	0%	100%	0%	0%	0%	0%	0%
Int'l-014	Gold Coast, Queensland, Australia	76%	1%	14%	0%	5%	4%	0%
Int'l-256	Stellenbosch, South Africa	0%	0%	0%	99%	1%	0%	0%
Int'l-284	Ajman, United Arab Emirates	0%	2%	98%	0%	0%	0%	0%
Int'l-230	Berdsk, Novosibirskaya, Russia	20%	2%	57%	0%	20%	0%	0%
Int'l-064	Heze, Shandong, China	99%	1%	0%	0%	0%	0%	0%
Int'l-159	Naples, Campania, Italy	12%	7%	40%	0%	22%	19%	0%
Int'l-063	Coquimbo, Elqui, Chile	0%	0%	0%	0%	86%	14%	0%
Int'l-139	Narasapur, India	82%	3%	15%	0%	0%	0%	0%
Int'l-103	Dessie, Amhara, Ethiopia	0%	100%	0%	0%	0%	0%	0%
Int'l-113	Châteauroux, Centre, France	1%	0%	1%	95%	3%	1%	0%
Int'l-167	Ōita, Japan	23%	7%	23%	42%	5%	0%	0%
Int'l-084	Sabanalarga, Atlántico, Colombia	27%	2%	71%	0%	0%	0%	0%

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[2] The data in this table are represented in Figure 18 in this appendix, page 109.

Table 12. Annual electricity requirements and coast in the 25 locations in the study site

Project ID[3]	Locations Info	ASHREA Climate Zone	Annual Electricity Requirements (MWh)	Annual Electricity Costs from Grid ($)
Nat'l- 098	Sodus, New York, United States	5A	540	$75,644
Nat'l- 077	Honokaa, Hawaii, United States	2A	628	$213,688
Nat’l-035	Farragut, Iowa, United States	5A	596	$41,748
Nat’l-099	Phoenix, Arizona, United States	2B	699	$62,930
Nat’l-075	Annapolis, California, United States	3C	554	$66,456
Int’l-056	Fort McMurray, Alberta, Canada	7	556	$55,623
Int’l-106	Vantaa, Southern Finland, Finland	6A	548	$54,780
Int’l-037	Barreiras, Bahia, Brazil	1A	501	$75,141
Int’l-280	Söke, Aydın, Turkey	3A	625	$87,437
Int’l-151	Banjar, Bali, Indonesia	2A	631	$37,877
Int’l-214	Makurdi, Benue, Nigeria	1A	789	$71,030
Int’l-289	Belfast, United Kingdom	5A	501	$75,141
Int’l-192	Nouakchott, Mauritania	1B	734	$66,084
Int’l-014	Gold Coast, Queensland, Australia	2A	645	$38,709
Int’l-256	Stellenbosch, South Africa	3C	572	$11,450
Int’l-284	Ajman, United Arab Emirates	1B	820	$73,806
Int’l-230	Berdsk, Novosibirskaya, Russia	7	553	$27,659
Int'l-064	Heze, Shandong, China	3A	640	$57,638
Int’l-159	Naples, Campania, Italy	3A	615	$172,069
Int’l-063	Coquimbo, Elqui, Chile	3C	562	$78,666
Int’l-139	Narasapur, India	1A	774	$61,940
Int’l-103	Dessie, Amhara, Ethiopia	3C	585	$52,632
Int’l-113	Châteauroux, Centre, France	4A	565	$62,203
Int’l-167	Ōita, Japan	3C	597	$95,496
Int’l-084	Sabanalarga, Atlántico, Colombia	1A	792	$102,911

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[3] The data in this table are represented in Figure 11 in chapter 4 page 58.

Table 13. Annual on-site electricity production from PV and wind-turbines in all locations

Project ID[4]	Locations Info	Annual On-site Produced from PV (kWh)	Annual On-site Produced from Wind-Turbines (kWh)	Annual Saving Costs from Renewables ($)
Nat'l- 098	Sodus, New York, United States	222,706	46,835	$37,736
Nat'l- 077	Honokaa, Hawaii, United States	417,330	1,000	$142,232
Nat’l-035	Farragut, Iowa, United States	-	-	$-
Nat’l-099	Phoenix, Arizona, United States	255,068	2,235	$23,157
Nat’l-075	Annapolis, California, United States	295,196	4,520	$35,966
Int’l-056	Fort McMurray, Alberta, Canada	107,923	2,040	$10,996
Int’l-106	Vantaa, Southern Finland, Finland	-	-	-
Int’l-037	Barreiras, Bahia, Brazil	87,292	16,615	$15,586
Int’l-280	Söke, Aydın, Turkey	333,990	7,975	$47,875
Int’l-151	Banjar, Bali, Indonesia	-	-	-
Int’l-214	Makurdi, Benue, Nigeria	298,469	1,200	$26,970
Int’l-289	Belfast, United Kingdom	87,292	16,615	$15,586
Int’l-192	Nouakchott, Mauritania	324,024	21,690	$31,114
Int’l-014	Gold Coast, Queensland, Australia	185,575	12,025	$11,856
Int’l-256	Stellenbosch, South Africa	-	-	-
Int’l-284	Ajman, United Arab Emirates	309,252	6,380	$28,407
Int’l-230	Berdsk, Novosibirskaya, Russia	-	-	-
Int'l-064	Heze, Shandong, China	182,489	3,650	$16,753
Int’l-159	Naples, Campania, Italy	335,756	5,930	$95,672
Int’l-063	Coquimbo, Elqui, Chile	414,174	4,350	$58,593
Int’l-139	Narasapur, India	175,796	4,340	$14,411
Int’l-103	Dessie, Amhara, Ethiopia	328,267	8,015	$30,265
Int’l-113	Châteauroux, Centre, France	134,160	8,905	$15,737
Int’l-167	Ōita, Japan	263,275	3,620	$42,703
Int’l-084	Sabanalarga, Atlántico, Colombia	361,276	3,235	$47,386

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[4] The data in this table are represented in Figure 11 in chapter 4 page 58.

Table 14. On-site production contribution to the building's electricity requirements

Project ID[5]	Locations Info	PV production to the building's requirements	Wind production to the building's requirements
Nat'l- 098	Sodus, New York, United States	41%	9%
Nat'l- 077	Honokaa, Hawaii, United States	66%	0%
Nat'l-035	Farragut, Iowa, United States	0%	0%
Nat'l-099	Phoenix, Arizona, United States	36%	0%
Nat'l-075	Annapolis, California, United States	53%	1%
Int'l-056	Fort McMurray, Alberta, Canada	19%	0%
Int'l-106	Vantaa, Southern Finland, Finland	0%	0%
Int'l-037	Barreiras, Bahia, Brazil	17%	3%
Int'l-280	Söke, Aydın, Turkey	53%	1%
Int'l-151	Banjar, Bali, Indonesia	0%	0%
Int'l-214	Makurdi, Benue, Nigeria	38%	0%
Int'l-289	Belfast, United Kingdom	17%	3%
Int'l-192	Nouakchott, Mauritania	44%	3%
Int'l-014	Gold Coast, Queensland, Australia	29%	2%
Int'l-256	Stellenbosch, South Africa	0%	0%
Int'l-284	Ajman, United Arab Emirates	38%	1%
Int'l-230	Berdsk, Novosibirskaya, Russia	0%	0%
Int'l-064	Heze, Shandong, China	28%	1%
Int'l-159	Naples, Campania, Italy	55%	1%
Int'l-063	Coquimbo, Elqui, Chile	74%	1%
Int'l-139	Narasapur, India	23%	1%
Int'l-103	Dessie, Amhara, Ethiopia	56%	1%
Int'l-113	Châteauroux, Centre, France	24%	2%
Int'l-167	Ōita, Japan	44%	1%
Int'l-084	Sabanalarga, Atlántico, Colombia	46%	0%

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[5] The data in this table are represented in Figure 11 in chapter 4 page 58.

Table 15. Photovoltaic analysis; installed panel area and cost; payback period

Project I[6]D	Locations Info	Total PV Installed Panel Area (ft^2)	Total PV Installed Panel Cost ($)	Total PV Payback Period (years)
Nat'l- 098	Sodus, New York, United States	18,208	$1,868,505	39
Nat'l- 077	Honokaa, Hawaii, United States	27,387	$3,315,755	19
Nat’l-035	Farragut, Iowa, United States	-	-	51
Nat’l-099	Phoenix, Arizona, United States	12,778	$1,311,278	39
Nat’l-075	Annapolis, California, United States	18,081	$1,855,472	36
Int’l-056	Fort McMurray, Alberta, Canada	8,669	$889,613	48
Int’l-106	Vantaa, Southern Finland, Finland	-	$-	56
Int’l-037	Barreiras, Bahia, Brazil	19,907	$2,042,856	33
Int’l-280	Söke, Aydın, Turkey	21,743	$2,231,267	34
Int’l-151	Banjar, Bali, Indonesia	-	-	61
Int’l-214	Makurdi, Benue, Nigeria	15,333	$1,573,472	38
Int’l-289	Belfast, United Kingdom	9,479	$972,735	46
Int’l-192	Nouakchott, Mauritania	16,079	$1,650,027	37
Int’l-014	Gold Coast, Queensland, Australia	8,880	$911,266	48
Int’l-256	Stellenbosch, South Africa	-	-	87
Int’l-284	Ajman, United Arab Emirates	16,012	$1,643,151	38
Int’l-230	Berdsk, Novosibirskaya, Russia	-	-	80
Int'l-064	Heze, Shandong, China	11,063	$1,135,285	42
Int’l-159	Naples, Campania, Italy	27,564	$2,828,618	24
Int’l-063	Coquimbo, Elqui, Chile	24,866	$2,551,749	31
Int’l-139	Narasapur, India	9,446	$969,349	43
Int’l-103	Dessie, Amhara, Ethiopia	15,520	$1,592,662	36
Int’l-113	Châteauroux, Centre, France	10,253	$1,052,163	45
Int’l-167	Ōita, Japan	20,916	$2,146,400	36
Int’l-084	Sabanalarga, Atlántico, Colombia	21,745	$2,231,472	34

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[6] The data in this table are represented in Figure 11 and Figure 12 in chapter 4 pages 58 and 61.

Table 16. Annual Life Cycle CO2 equivalent emissions in the 25 locations included in the study

Project ID[7]	Locations Info	Grid Electricity[8] (Annual kg CO_2 eq)	Production[9] (Annual kg CO_2 eq)	On-site Systems[10] (Life-cycle kg CO_2 eq)
Nat'l- 098	Sodus, New York, United States	171,606	(85,607)	36,416
Nat'l- 077	Honokaa, Hawaii, United States	428,751	(210,154)	64,622
Nat’l-035	Farragut, Iowa, United States	504,696	-	-
Nat’l-099	Phoenix, Arizona, United States	497,106	(182,927)	25,556
Nat’l-075	Annapolis, California, United States	262,614	(142,127)	36,162
Int’l-056	Fort McMurray, Alberta, Canada	577,125	(114,094)	17,338
Int’l-106	Vantaa, Southern Finland, Finland	314,685	-	-
Int’l-037	Barreiras, Bahia, Brazil	2,244	(466)	39,814
Int’l-280	Söke, Aydın, Turkey	518,189	(283,727)	43,486
Int’l-151	Banjar, Bali, Indonesia	585,978	-	-
Int’l-214	Makurdi, Benue, Nigeria	569,091	(216,086)	30,666
Int’l-289	Belfast, United Kingdom	401,362	(83,252)	18,958
Int’l-192	Nouakchott, Mauritania	625,959	(294,718)	32,158
Int’l-014	Gold Coast, Queensland, Australia	652,659	(199,900)	17,760
Int’l-256	Stellenbosch, South Africa	5,219	-	-
Int’l-284	Ajman, United Arab Emirates	573,376	(220,684)	32,024
Int’l-230	Berdsk, Novosibirskaya, Russia	363,195	-	-
Int'l-064	Heze, Shandong, China	759,588	(220,773)	22,126
Int’l-159	Naples, Campania, Italy	302,901	(168,416)	55,128
Int’l-063	Coquimbo, Elqui, Chile	5,721	(4,261)	49,732
Int’l-139	Narasapur, India	851,427	(198,091)	18,892
Int’l-103	Dessie, Amhara, Ethiopia	498,533	(286,677)	31,040
Int’l-113	Châteauroux, Centre, France	14,353	(3,631)	20,506
Int’l-167	Ōita, Japan	296,800	(129,120)	41,832
Int’l-084	Sabanalarga, Atlántico, Colombia	658,942	(303,417)	43,490

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[7] The data in this table are represented in Figure 12 in chapter 4 page 61.
[8] The annual impact from the annual grid electricity consumption.
[9] The annual impacts can be mitigated by using PV and Wind systems on-site.
[10] The impact from the systems on-site comprising the entire system cradle-to-grave life cycle.

APPENDIX C

SUPPLEMENTARY DATA FOR WHOLE-BUILDING LCA

This Appendix (C) shows the full data related to chapter 5. It comprises all simulation and modeling data related to the building of Magee-Womens Hospital (MWH).

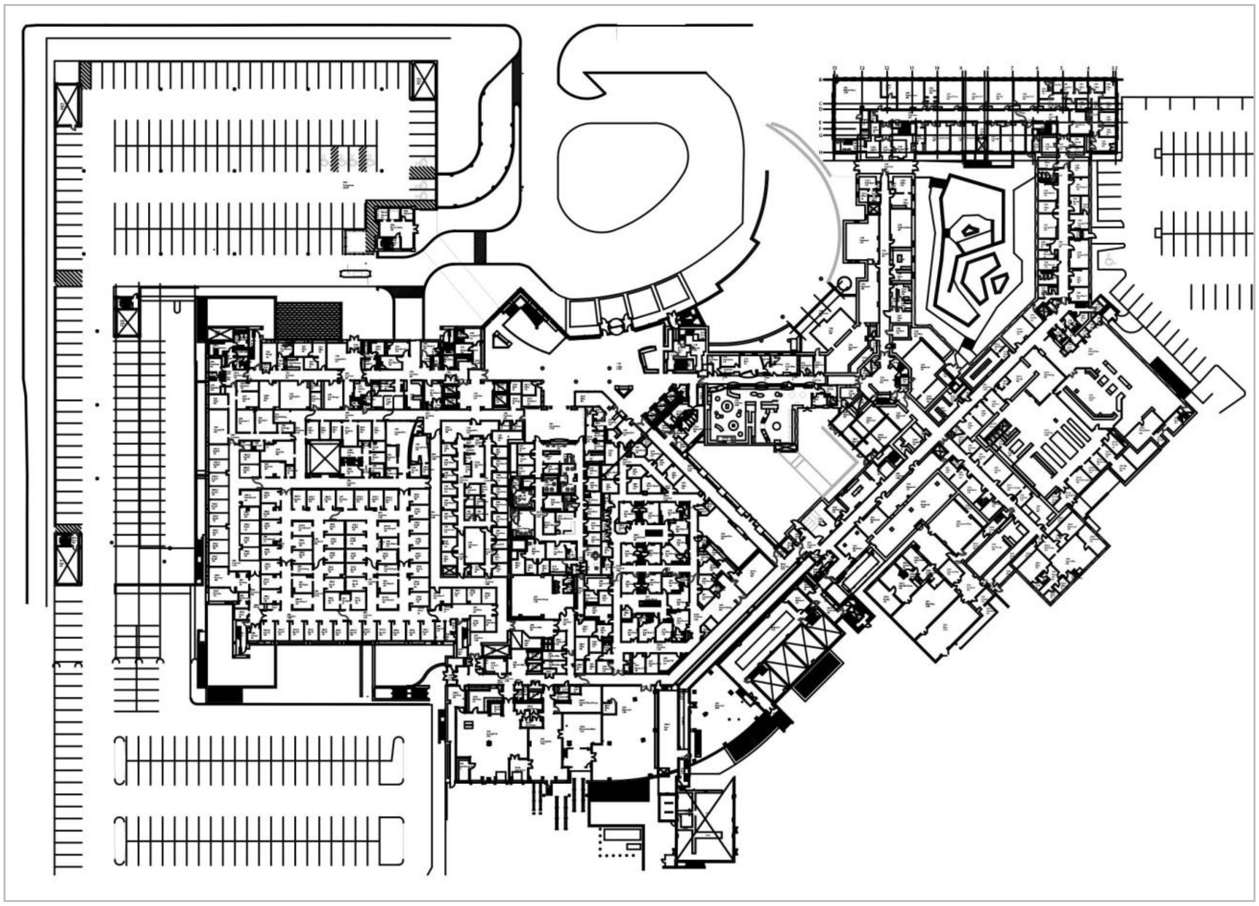
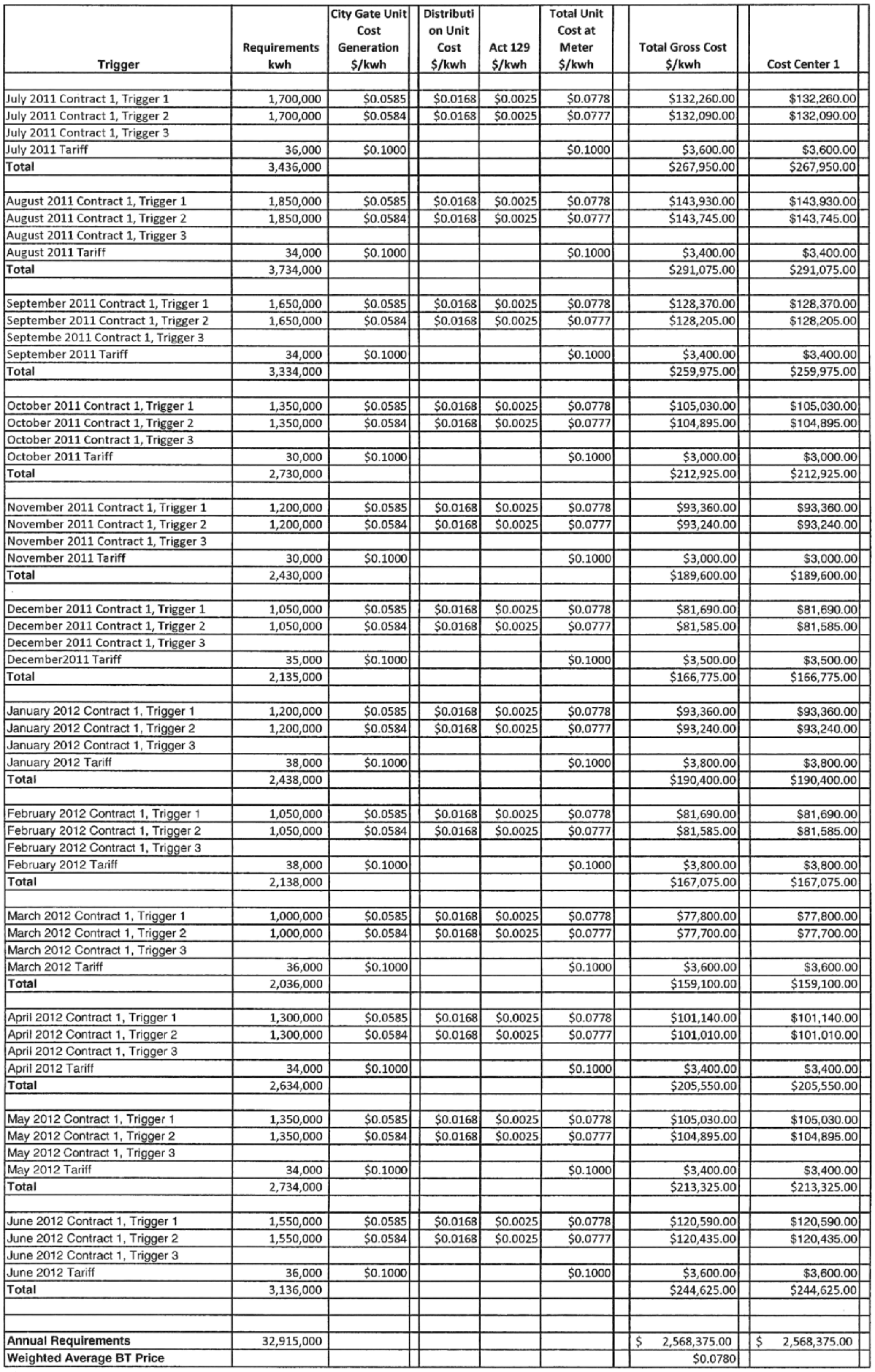


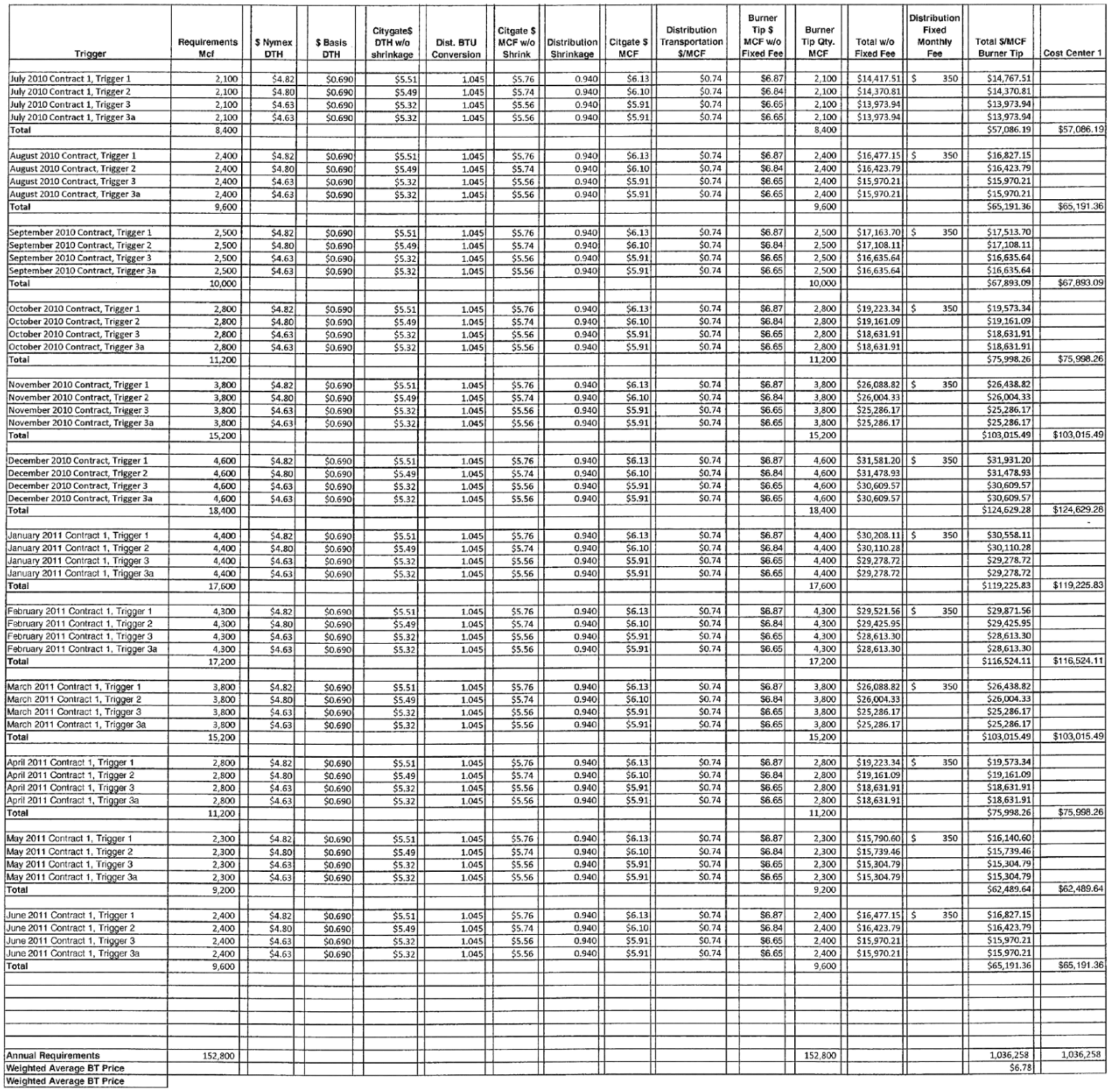
Figure 19. Sample floor plan of MWH – Main - Level 1

Table 17. MWH annual electricity consumption (actual)

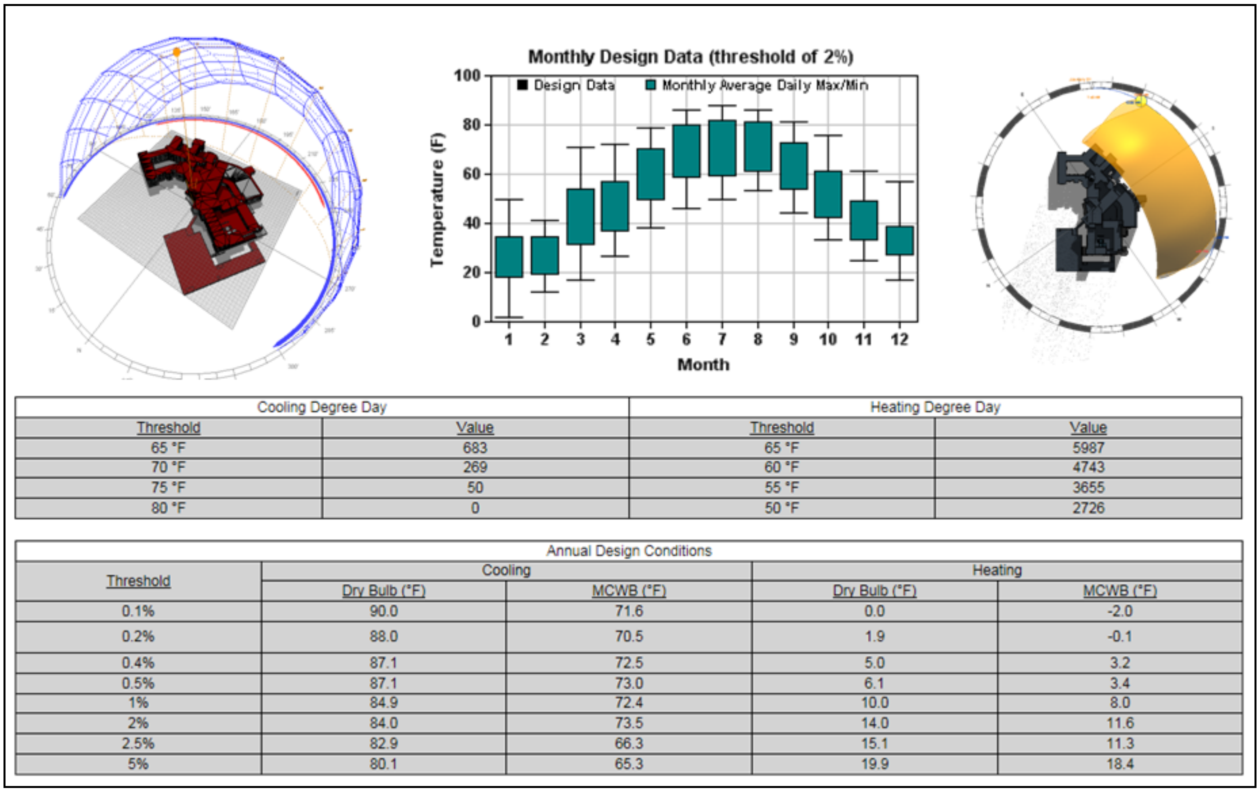


Trigger	Requirements kwh	City Gate Unit Cost Generation $/kwh	Distribution Unit Cost $/kwh	Act 129 $/kwh	Total Unit Cost at Meter $/kwh	Total Gross Cost $/kwh	Cost Center 1
July 2011 Contract 1, Trigger 1	1,700,000	$0.0585	$0.0168	$0.0025	$0.0778	$132,260.00	$132,260.00
July 2011 Contract 1, Trigger 2	1,700,000	$0.0584	$0.0168	$0.0025	$0.0777	$132,090.00	$132,090.00
July 2011 Contract 1, Trigger 3							
July 2011 Tariff	36,000	$0.1000			$0.1000	$3,600.00	$3,600.00
Total	3,436,000					$267,950.00	$267,950.00
August 2011 Contract 1, Trigger 1	1,850,000	$0.0585	$0.0168	$0.0025	$0.0778	$143,930.00	$143,930.00
August 2011 Contract 1, Trigger 2	1,850,000	$0.0584	$0.0168	$0.0025	$0.0777	$143,745.00	$143,745.00
August 2011 Contract 1, Trigger 3							
August 2011 Tariff	34,000	$0.1000			$0.1000	$3,400.00	$3,400.00
Total	3,734,000					$291,075.00	$291,075.00
September 2011 Contract 1, Trigger 1	1,650,000	$0.0585	$0.0168	$0.0025	$0.0778	$128,370.00	$128,370.00
September 2011 Contract 1, Trigger 2	1,650,000	$0.0584	$0.0168	$0.0025	$0.0777	$128,205.00	$128,205.00
Septembe 2011 Contract 1, Trigger 3							
September 2011 Tariff	34,000	$0.1000			$0.1000	$3,400.00	$3,400.00
Total	3,334,000					$259,975.00	$259,975.00
October 2011 Contract 1, Trigger 1	1,350,000	$0.0585	$0.0168	$0.0025	$0.0778	$105,030.00	$105,030.00
October 2011 Contract 1, Trigger 2	1,350,000	$0.0584	$0.0168	$0.0025	$0.0777	$104,895.00	$104,895.00
October 2011 Contract 1, Trigger 3							
October 2011 Tariff	30,000	$0.1000			$0.1000	$3,000.00	$3,000.00
Total	2,730,000					$212,925.00	$212,925.00
November 2011 Contract 1, Trigger 1	1,200,000	$0.0585	$0.0168	$0.0025	$0.0778	$93,360.00	$93,360.00
November 2011 Contract 1, Trigger 2	1,200,000	$0.0584	$0.0168	$0.0025	$0.0777	$93,240.00	$93,240.00
November 2011 Contract 1, Trigger 3							
November 2011 Tariff	30,000	$0.1000			$0.1000	$3,000.00	$3,000.00
Total	2,430,000					$189,600.00	$189,600.00
December 2011 Contract 1, Trigger 1	1,050,000	$0.0585	$0.0168	$0.0025	$0.0778	$81,690.00	$81,690.00
December 2011 Contract 1, Trigger 2	1,050,000	$0.0584	$0.0168	$0.0025	$0.0777	$81,585.00	$81,585.00
December 2011 Contract 1, Trigger 3							
December2011 Tariff	35,000	$0.1000			$0.1000	$3,500.00	$3,500.00
Total	2,135,000					$166,775.00	$166,775.00
January 2012 Contract 1, Trigger 1	1,200,000	$0.0585	$0.0168	$0.0025	$0.0778	$93,360.00	$93,360.00
January 2012 Contract 1, Trigger 2	1,200,000	$0.0584	$0.0168	$0.0025	$0.0777	$93,240.00	$93,240.00
January 2012 Contract 1, Trigger 3							
January 2012 Tariff	38,000	$0.1000			$0.1000	$3,800.00	$3,800.00
Total	2,438,000					$190,400.00	$190,400.00
February 2012 Contract 1, Trigger 1	1,050,000	$0.0585	$0.0168	$0.0025	$0.0778	$81,690.00	$81,690.00
February 2012 Contract 1, Trigger 2	1,050,000	$0.0584	$0.0168	$0.0025	$0.0777	$81,585.00	$81,585.00
February 2012 Contract 1, Trigger 3							
February 2012 Tariff	38,000	$0.1000			$0.1000	$3,800.00	$3,800.00
Total	2,138,000					$167,075.00	$167,075.00
March 2012 Contract 1, Trigger 1	1,000,000	$0.0585	$0.0168	$0.0025	$0.0778	$77,800.00	$77,800.00
March 2012 Contract 1, Trigger 2	1,000,000	$0.0584	$0.0168	$0.0025	$0.0777	$77,700.00	$77,700.00
March 2012 Contract 1, Trigger 3							
March 2012 Tariff	36,000	$0.1000			$0.1000	$3,600.00	$3,600.00
Total	2,036,000					$159,100.00	$159,100.00
April 2012 Contract 1, Trigger 1	1,300,000	$0.0585	$0.0168	$0.0025	$0.0778	$101,140.00	$101,140.00
April 2012 Contract 1, Trigger 2	1,300,000	$0.0584	$0.0168	$0.0025	$0.0777	$101,010.00	$101,010.00
April 2012 Contract 1, Trigger 3							
April 2012 Tariff	34,000	$0.1000			$0.1000	$3,400.00	$3,400.00
Total	2,634,000					$205,550.00	$205,550.00
May 2012 Contract 1, Trigger 1	1,350,000	$0.0585	$0.0168	$0.0025	$0.0778	$105,030.00	$105,030.00
May 2012 Contract 1, Trigger 2	1,350,000	$0.0584	$0.0168	$0.0025	$0.0777	$104,895.00	$104,895.00
May 2012 Contract 1, Trigger 3							
May 2012 Tariff	34,000	$0.1000			$0.1000	$3,400.00	$3,400.00
Total	2,734,000					$213,325.00	$213,325.00
June 2012 Contract 1, Trigger 1	1,550,000	$0.0585	$0.0168	$0.0025	$0.0778	$120,590.00	$120,590.00
June 2012 Contract 1, Trigger 2	1,550,000	$0.0584	$0.0168	$0.0025	$0.0777	$120,435.00	$120,435.00
June 2012 Contract 1, Trigger 3							
June 2012 Tariff	36,000	$0.1000			$0.1000	$3,600.00	$3,600.00
Total	3,136,000					$244,625.00	$244,625.00
Annual Requirements	32,915,000					$ 2,568,375.00	$ 2,568,375.00
Weighted Average BT Price						$0.0780	

Table 18. MWH annual fuel on-site - natural gas consumption (actual)



Trigger	Requirements Mcf	$ Nymex DTH	$ Basis DTH	Citygate$ DTH w/o shrinkage	Dist. BTU Conversion	Citgate $ MCF w/o Shrink	Distribution Shrinkage	Citgate $ MCF	Distribution Transportation $/MCF	Burner Tip $ MCF w/o Fixed Fee	Burner Tip Qty. MCF	Total w/o Fixed Fee	Distribution Fixed Monthly Fee	Total $/MCF Burner Tip	Cost Center 1
July 2010 Contract 1, Trigger 1	2,100	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	2,100	$14,417.51	$ 350	$14,767.51	
July 2010 Contract 1, Trigger 2	2,100	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	2,100	$14,370.81		$14,370.81	
July 2010 Contract 1, Trigger 3	2,100	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,100	$13,973.94		$13,973.94	
July 2010 Contract 1, Trigger 3a	2,100	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,100	$13,973.94		$13,973.94	
Total	8,400										8,400			$57,086.19	$57,086.19
August 2010 Contract, Trigger 1	2,400	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	2,400	$16,477.15	$ 350	$16,827.15	
August 2010 Contract, Trigger 2	2,400	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	2,400	$16,423.79		$16,423.79	
August 2010 Contract, Trigger 3	2,400	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,400	$15,970.21		$15,970.21	
August 2010 Contract, Trigger 3a	2,400	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,400	$15,970.21		$15,970.21	
Total	9,600										9,600			$65,191.36	$65,191.36
September 2010 Contract, Trigger 1	2,500	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	2,500	$17,163.70	$ 350	$17,513.70	
September 2010 Contract, Trigger 2	2,500	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	2,500	$17,108.11		$17,108.11	
September 2010 Contract, Trigger 3	2,500	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,500	$16,635.64		$16,635.64	
September 2010 Contract, Trigger 3a	2,500	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,500	$16,635.64		$16,635.64	
Total	10,000										10,000			$67,893.09	$67,893.09
October 2010 Contract, Trigger 1	2,800	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	2,800	$19,223.34	$ 350	$19,573.34	
October 2010 Contract, Trigger 2	2,800	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	2,800	$19,161.09		$19,161.09	
October 2010 Contract, Trigger 3	2,800	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,800	$18,631.91		$18,631.91	
October 2010 Contract, Trigger 3a	2,800	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,800	$18,631.91		$18,631.91	
Total	11,200										11,200			$75,998.26	$75,998.26
November 2010 Contract, Trigger 1	3,800	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	3,800	$26,088.82	$ 350	$26,438.82	
November 2010 Contract, Trigger 2	3,800	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	3,800	$26,004.33		$26,004.33	
November 2010 Contract, Trigger 3	3,800	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	3,800	$25,286.17		$25,286.17	
November 2010 Contract, Trigger 3a	3,800	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	3,800	$25,286.17		$25,286.17	
Total	15,200										15,200			$103,015.49	$103,015.49
December 2010 Contract, Trigger 1	4,600	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	4,600	$31,581.20	$ 350	$31,931.20	
December 2010 Contract, Trigger 2	4,600	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	4,600	$31,478.93		$31,478.93	
December 2010 Contract, Trigger 3	4,600	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	4,600	$30,609.57		$30,609.57	
December 2010 Contract, Trigger 3a	4,600	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	4,600	$30,609.57		$30,609.57	
Total	18,400										18,400			$124,629.28	$124,629.28
															-
January 2011 Contract 1, Trigger 1	4,400	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	4,400	$30,208.11	$ 350	$30,558.11	
January 2011 Contract 1, Trigger 2	4,400	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	4,400	$30,110.28		$30,110.28	
January 2011 Contract 1, Trigger 3	4,400	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	4,400	$29,278.72		$29,278.72	
January 2011 Contract 1, Trigger 3a	4,400	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	4,400	$29,278.72		$29,278.72	
Total	17,600										17,600			$119,225.83	$119,225.83
February 2011 Contract 1, Trigger 1	4,300	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	4,300	$29,521.56	$ 350	$29,871.56	
February 2011 Contract 1, Trigger 2	4,300	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	4,300	$29,425.95		$29,425.95	
February 2011 Contract 1, Trigger 3	4,300	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	4,300	$28,613.30		$28,613.30	
February 2011 Contract 1, Trigger 3a	4,300	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	4,300	$28,613.30		$28,613.30	
Total	17,200										17,200			$116,524.11	$116,524.11
March 2011 Contract 1, Trigger 1	3,800	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	3,800	$26,088.82	$ 350	$26,438.82	
March 2011 Contract 1, Trigger 2	3,800	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	3,800	$26,004.33		$26,004.33	
March 2011 Contract 1, Trigger 3	3,800	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	3,800	$25,286.17		$25,286.17	
March 2011 Contract 1, Trigger 3a	3,800	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	3,800	$25,286.17		$25,286.17	
Total	15,200										15,200			$103,015.49	$103,015.49
April 2011 Contract 1, Trigger 1	2,800	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	2,800	$19,223.34	$ 350	$19,573.34	
April 2011 Contract 1, Trigger 2	2,800	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	2,800	$19,161.09		$19,161.09	
April 2011 Contract 1, Trigger 3	2,800	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,800	$18,631.91		$18,631.91	
April 2011 Contract 1, Trigger 3a	2,800	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,800	$18,631.91		$18,631.91	
Total	11,200										11,200			$75,998.26	$75,998.26
May 2011 Contract 1, Trigger 1	2,300	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	2,300	$15,790.60	$ 350	$16,140.60	
May 2011 Contract 1, Trigger 2	2,300	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	2,300	$15,739.46		$15,739.46	
May 2011 Contract 1, Trigger 3	2,300	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,300	$15,304.79		$15,304.79	
May 2011 Contract 1, Trigger 3a	2,300	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,300	$15,304.79		$15,304.79	
Total	9,200										9,200			$62,489.64	$62,489.64
June 2011 Contract 1, Trigger 1	2,400	$4.82	$0.690	$5.51	1.045	$5.76	0.940	$6.13	$0.74	$6.87	2,400	$16,477.15	$ 350	$16,827.15	
June 2011 Contract 1, Trigger 2	2,400	$4.80	$0.690	$5.49	1.045	$5.74	0.940	$6.10	$0.74	$6.84	2,400	$16,423.79		$16,423.79	
June 2011 Contract 1, Trigger 3	2,400	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,400	$15,970.21		$15,970.21	
June 2011 Contract 1, Trigger 3a	2,400	$4.63	$0.690	$5.32	1.045	$5.56	0.940	$5.91	$0.74	$6.65	2,400	$15,970.21		$15,970.21	
Total	9,600										9,600			$65,191.36	$65,191.36
Annual Requirements	152,800										152,800			1,036,258	1,036,258
Weighted Average BT Price														$6.78	
Weighted Average BT Price															



Cooling Degree Day		Heating Degree Day	
Threshold	Value	Threshold	Value
65 °F	683	65 °F	5987
70 °F	269	60 °F	4743
75 °F	50	55 °F	3655
80 °F	0	50 °F	2726

Annual Design Conditions

Threshold	Cooling		Heating	
	Dry Bulb (°F)	MCWB (°F)	Dry Bulb (°F)	MCWB (°F)
0.1%	90.0	71.6	0.0	-2.0
0.2%	88.0	70.5	1.9	-0.1
0.4%	87.1	72.5	5.0	3.2
0.5%	87.1	73.0	6.1	3.4
1%	84.9	72.4	10.0	8.0
2%	84.0	73.5	14.0	11.6
2.5%	82.9	66.3	15.1	11.3
5%	80.1	65.3	19.9	18.4

Figure 20. Annual and monthly design conditions for MWH

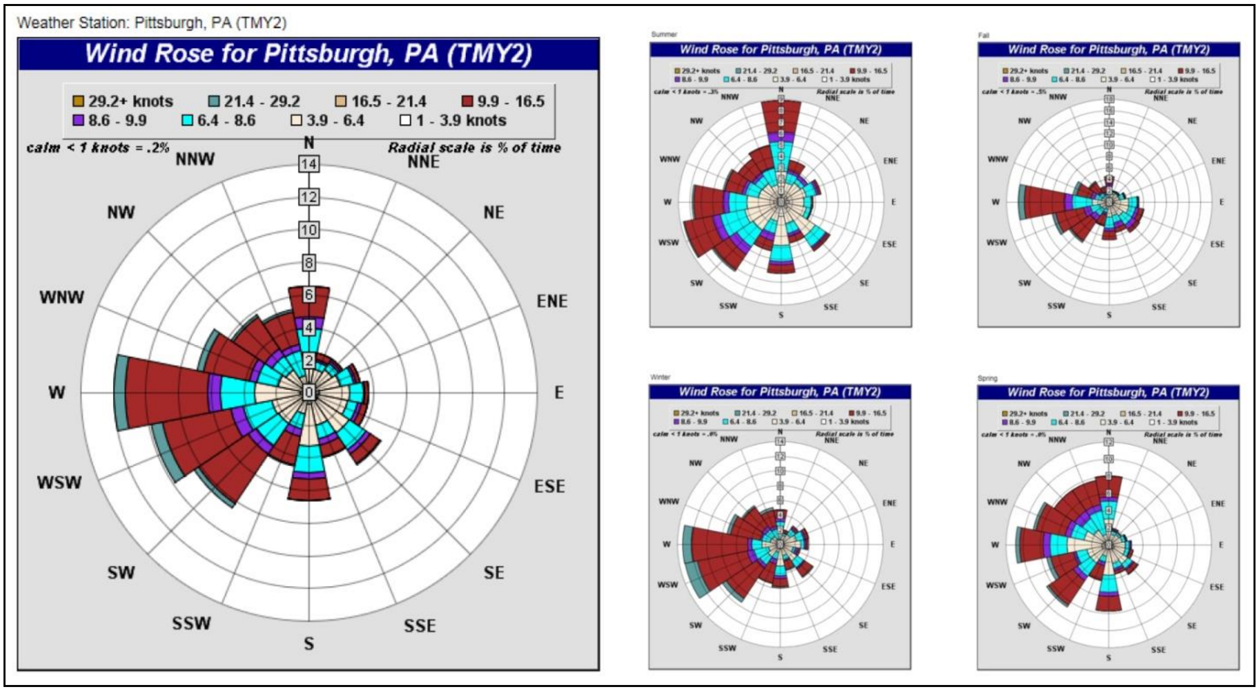


Figure 21. Annual and seasonal wind rose for MWH

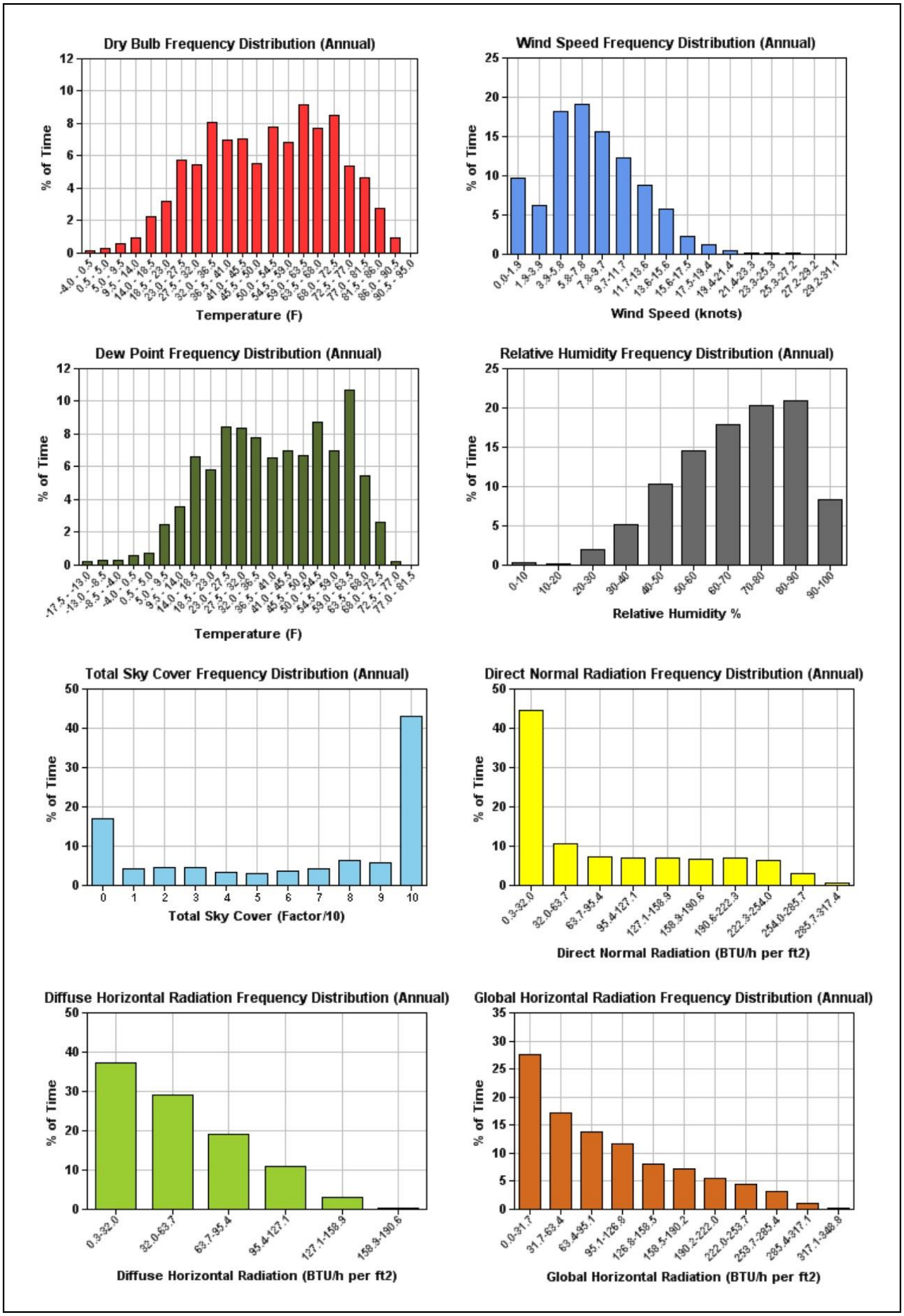
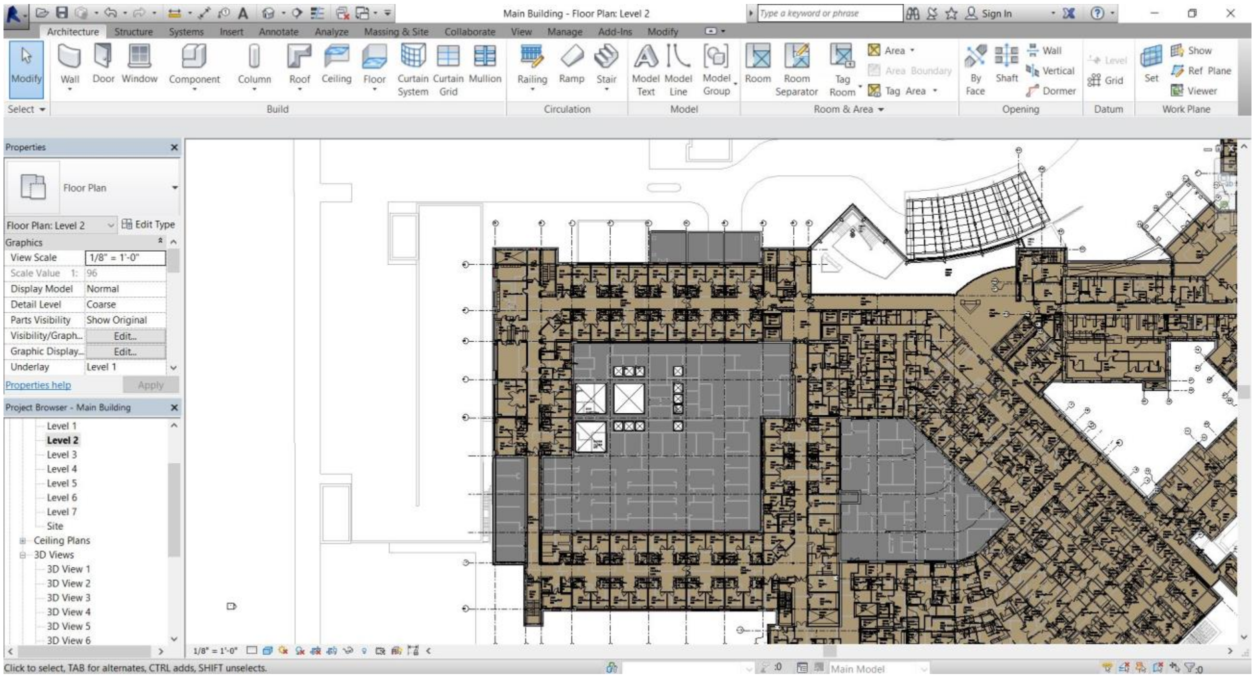


Figure 22. Weather summary representation for MWH



Floor Plan: Level 2

Graphics

View Scale: 1/8" = 1'-0"

Scale Value 1: 96

Display Model: Normal

Detail Level: Coarse

Parts Visibility: Show Original

Visibility/Graph...: Edit...

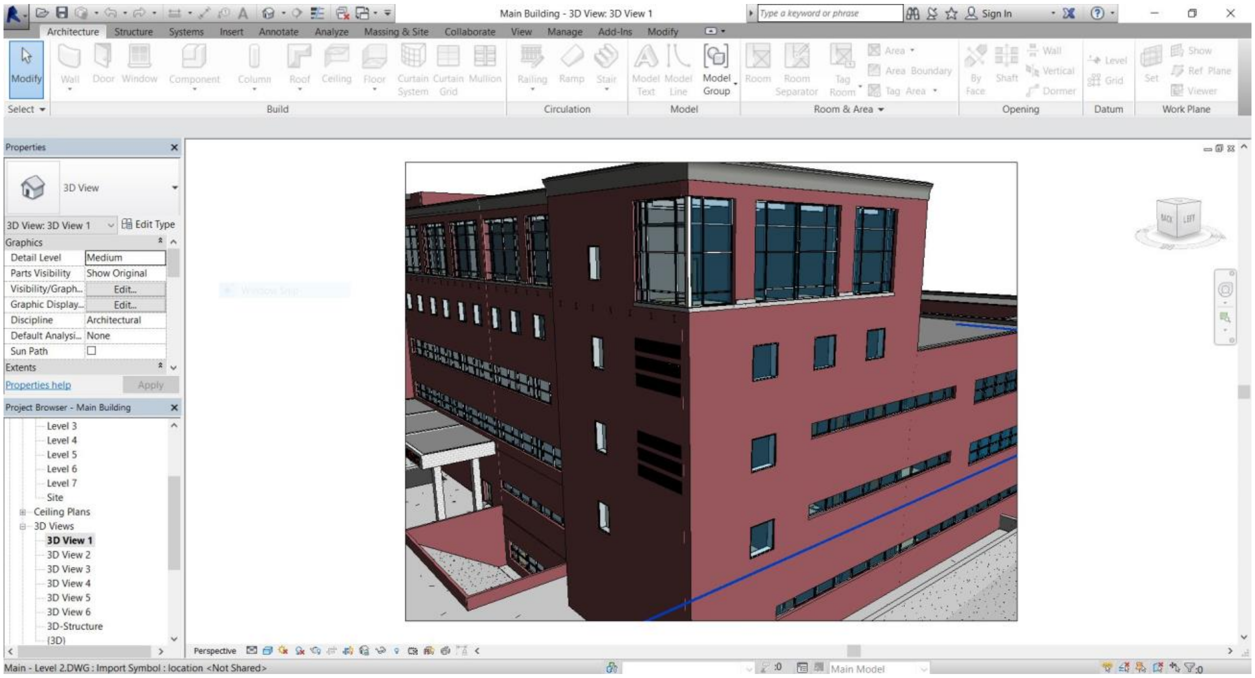
Graphic Display...: Edit...

Underlay: Level 1

1/8" = 1'-0"

Click to select, TAB for alternates, CTRL adds, SHIFT unselects.

Figure 23. The imported CAD and floor plans execution in BIM



3D View: 3D View 1

Graphics

Detail Level: Medium

Parts Visibility: Show Original

Visibility/Graph...: Edit...

Graphic Display...: Edit...

Discipline: Architectural

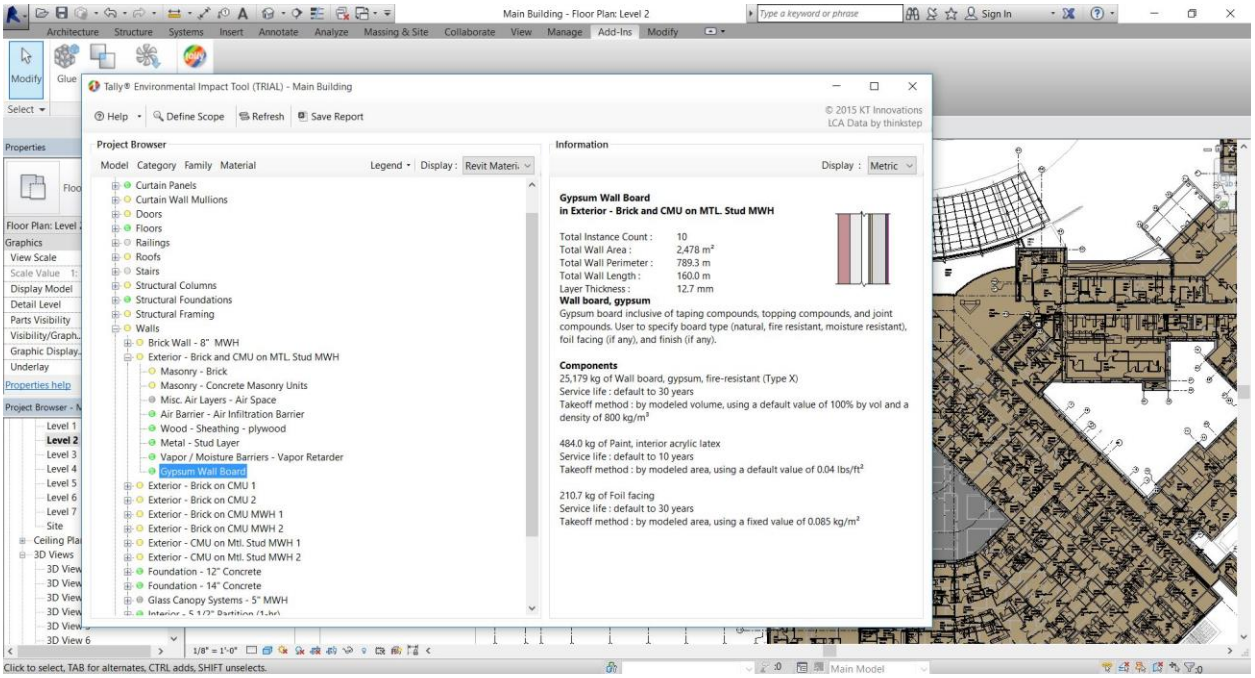
Default Analysi...: None

Sun Path: ☐

Extents

Main - Level 2.DWG : Import Symbol : location <Not Shared>

Figure 24. The development of MWH building in BIM



Gypsum Wall Board
in Exterior - Brick and CMU on MTL. Stud MWH

Total Instance Count :	10
Total Wall Area :	2,478 m²
Total Wall Perimeter :	789.3 m
Total Wall Length :	160.0 m
Layer Thickness :	12.7 mm

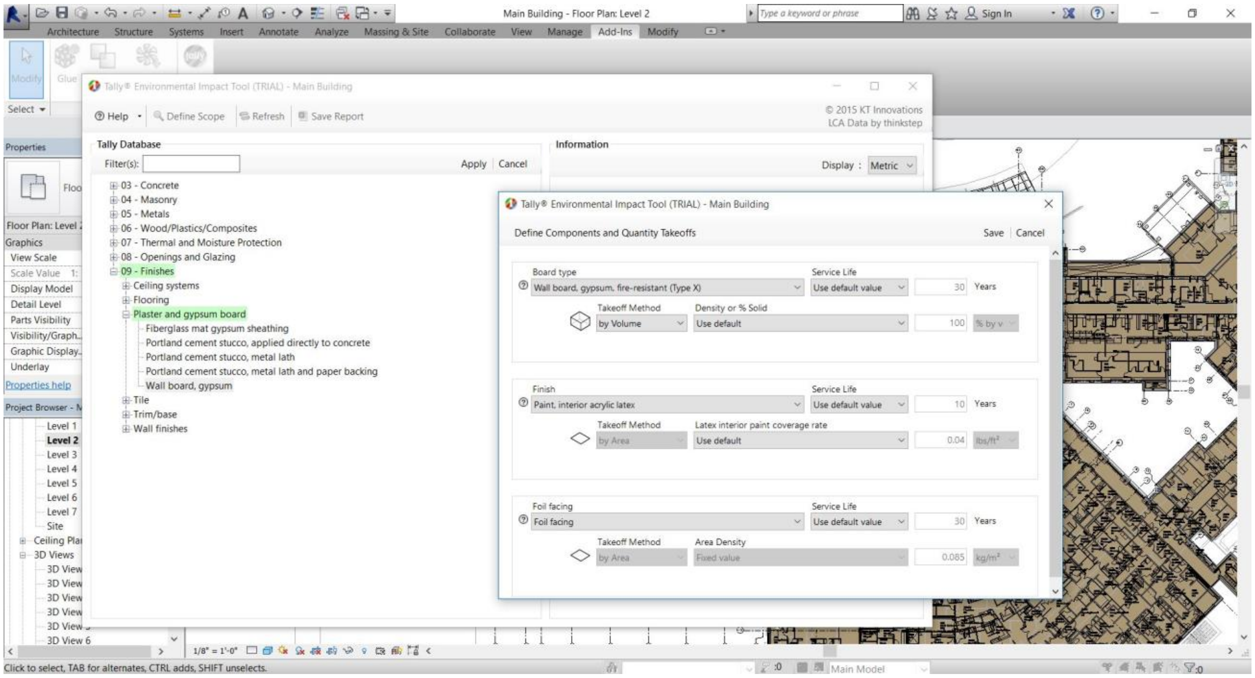
Wall board, gypsum
Gypsum board inclusive of taping compounds, topping compounds, and joint compounds. User to specify board type (natural, fire resistant, moisture resistant), foil facing (if any), and finish (if any).

Components
25,179 kg of Wall board, gypsum, fire-resistant (Type X)
Service life : default to 30 years
Takeoff method : by modeled volume, using a default value of 100% by vol and a density of 800 kg/m³

484.0 kg of Paint, interior acrylic latex
Service life : default to 10 years
Takeoff method : by modeled area, using a default value of 0.04 lbs/ft²

210.7 kg of Foil facing
Service life : default to 30 years
Takeoff method : by modeled area, using a fixed value of 0.085 kg/m²

Figure 25. Tally and MWH building elements within BIM environment

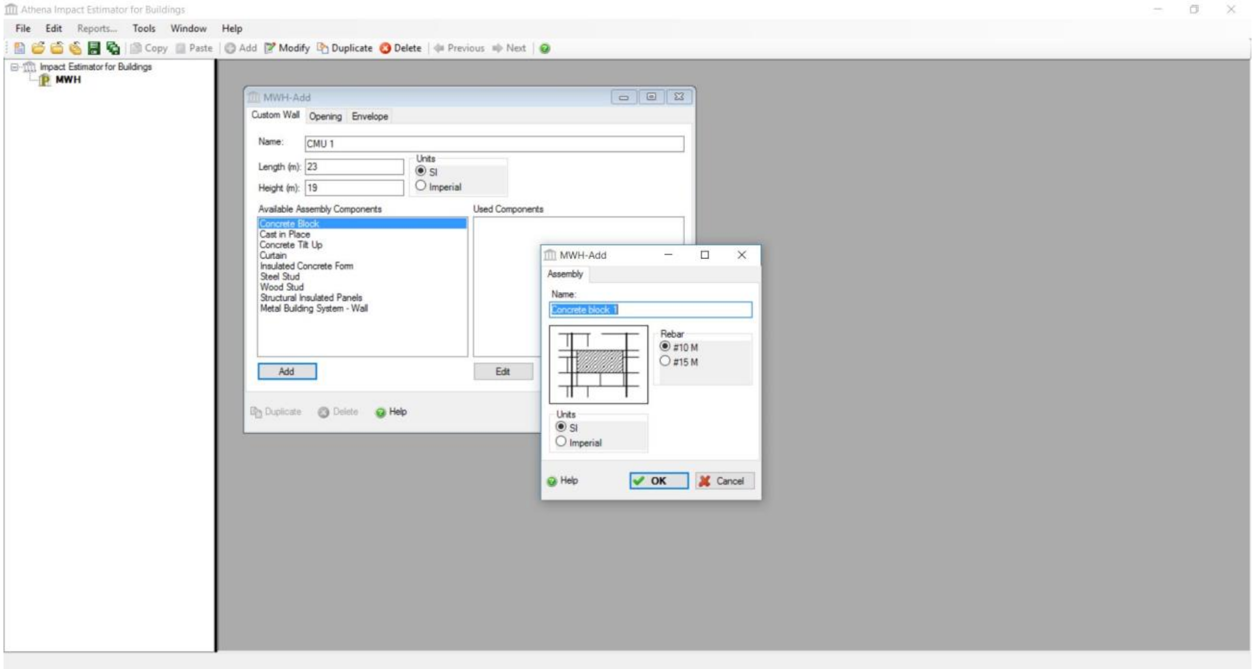


Board type: Wall board, gypsum, fire-resistant (Type X)
Service Life: Use default value — 30 Years
Takeoff Method: by Volume
Density or % Solid: Use default — 100 % by v

Finish: Paint, interior acrylic latex
Service Life: Use default value — 10 Years
Takeoff Method: by Area
Latex interior paint coverage rate: Use default — 0.04 lbs/ft²

Foil facing: Foil facing
Service Life: Use default value — 30 Years
Takeoff Method: by Area
Area Density: Fixed value — 0.085 kg/m²

Figure 26. Tally process of defining and matching materials



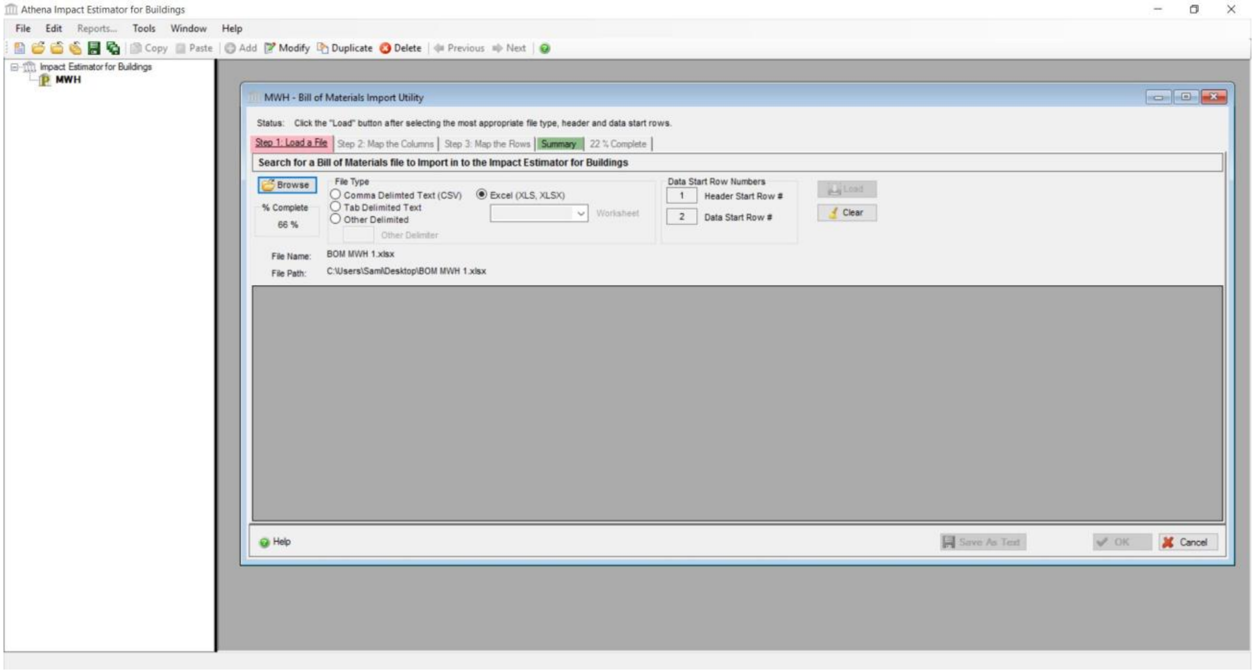
Name: CMU 1
Length (m): 23
Height (m): 19
Units: ● SI ○ Imperial

Available Assembly Components:
Concrete Block
Cast in Place
Concrete Tilt Up
Curtain
Insulated Concrete Form
Steel Stud
Wood Stud
Structural Insulated Panels
Metal Building System - Wall

Used Components

Name: Concrete block 1
Rebar: ● #10 M ○ #15 M
Units: ● SI ○ Imperial

Figure 27. Athena process of manually defining MWH building elements



Status: Click the "Load" button after selecting the most appropriate file type, header and data start rows.

Search for a Bill of Materials file to Import in to the Impact Estimator for Buildings

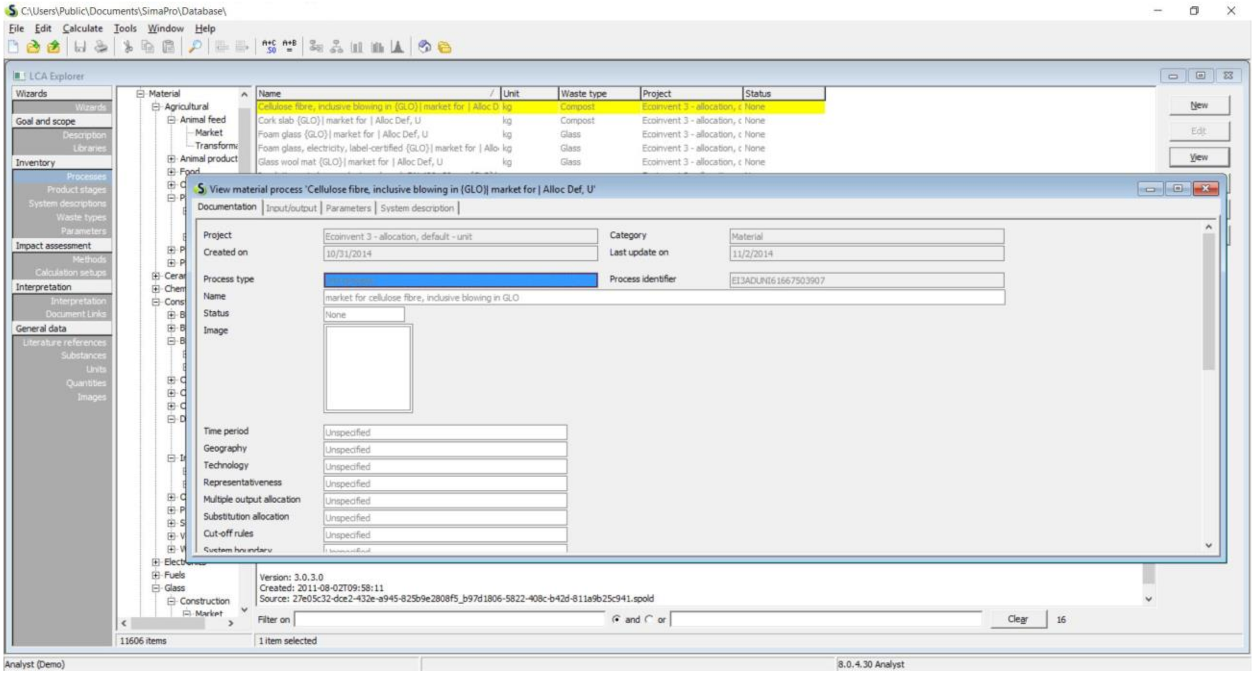
% Complete: 66 %

File Type:
○ Comma Delimted Text (CSV)
○ Tab Delimited Text
○ Other Delimited
Other Delimiter
● Excel (XLS, XLSX)
Worksheet

Data Start Row Numbers:
1 Header Start Row #
2 Data Start Row #

File Name: BOM MWH 1.xlsx
File Path: C:\Users\Sam\Desktop\BOM MWH 1.xlsx

Figure 28. Athena process of importing bill of materials from BIM



Name	Unit	Waste type	Project	Status
Cellulose fibre, inclusive blowing in {GLO}| market for | Alloc D	kg	Compost	Ecoinvent 3 - allocation, c	None
Cork slab {GLO}| market for | Alloc Def, U	kg	Compost	Ecoinvent 3 - allocation, c	None
Foam glass {GLO}| market for | Alloc Def, U	kg	Glass	Ecoinvent 3 - allocation, c	None
Foam glass, electricity, label-certified {GLO}| market for | Allo	kg	Glass	Ecoinvent 3 - allocation, c	None
Glass wool mat {GLO}| market for | Alloc Def, U	kg	Glass	Ecoinvent 3 - allocation, c	None

View material process 'Cellulose fibre, inclusive blowing in {GLO}| market for | Alloc Def, U'

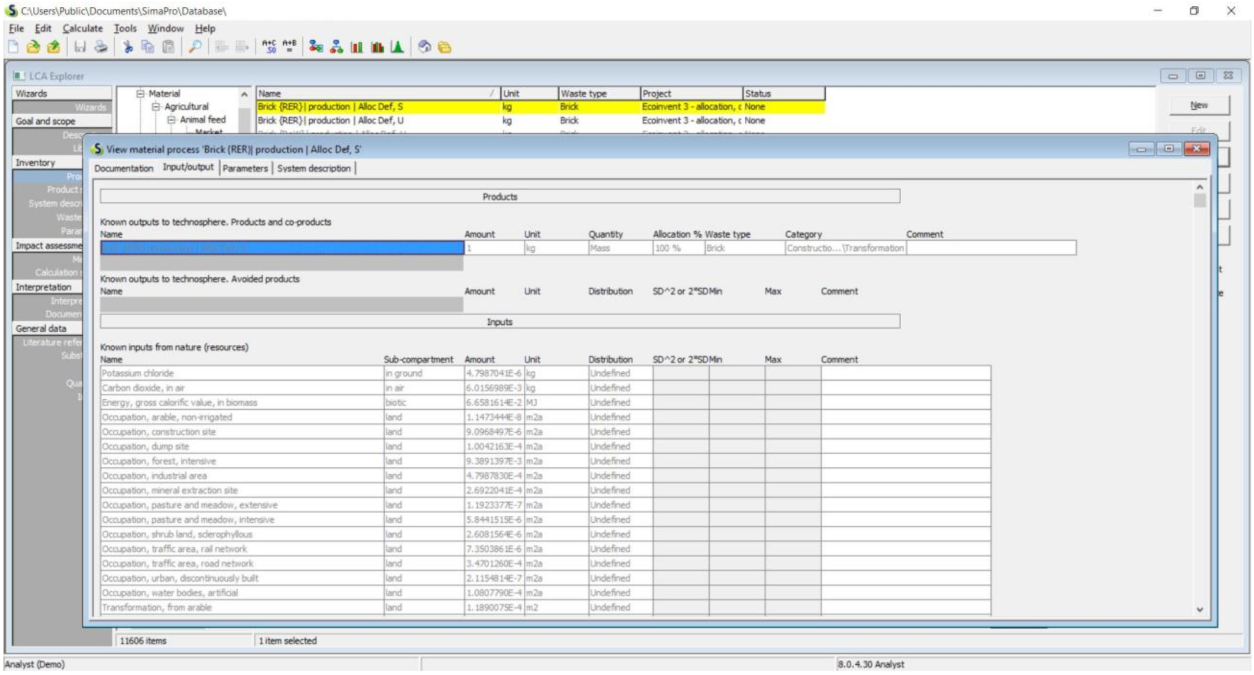
Project: Ecoinvent 3 - allocation, default - unit
Category: Material
Created on: 10/31/2014
Last update on: 11/2/2014
Process type:
Process identifier: EI3ADUNI61667503907
Name: market for cellulose fibre, inclusive blowing in GLO
Status: None
Image:
Time period: Unspecified
Geography: Unspecified
Technology: Unspecified
Representativeness: Unspecified
Multiple output allocation: Unspecified
Substitution allocation: Unspecified
Cut-off rules: Unspecified

Version: 3.0.3.0
Created: 2011-08-02T09:58:11
Source: 27e05c32-dce2-432e-a945-825b9e2808f5_b97d1806-5822-408c-b42d-811a9b25c941.spold

Filter on ◉ and ○ or 16

11606 items
1 item selected

Figure 29. SimaPro process of manually selecting and molding MWH building elements



Name	Unit	Waste type	Project	Status
Brick {RER}| production | Alloc Def, S	kg	Brick	Ecoinvent 3 - allocation, c	None
Brick {RER}| production | Alloc Def, U	kg	Brick	Ecoinvent 3 - allocation, c	None

View material process 'Brick {RER}| production | Alloc Def, S'

Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
	1	kg	Mass	100 %	Brick	Constructio...\Transformation	

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Potassium chloride	in ground	4.7987041E-6	kg	Undefined				
Carbon dioxide, in air	in air	6.0156989E-3	kg	Undefined				
Energy, gross calorific value, in biomass	biotic	6.6581614E-2	MJ	Undefined				
Occupation, arable, non-irrigated	land	1.1473444E-8	m2a	Undefined				
Occupation, construction site	land	9.0968497E-6	m2a	Undefined				
Occupation, dump site	land	1.0042163E-4	m2a	Undefined				
Occupation, forest, intensive	land	9.3891397E-3	m2a	Undefined				
Occupation, industrial area	land	4.7987830E-4	m2a	Undefined				
Occupation, mineral extraction site	land	2.6922041E-4	m2a	Undefined				
Occupation, pasture and meadow, extensive	land	1.1923377E-7	m2a	Undefined				
Occupation, pasture and meadow, intensive	land	5.8441515E-6	m2a	Undefined				
Occupation, shrub land, sclerophyllous	land	2.6081564E-6	m2a	Undefined				
Occupation, traffic area, rail network	land	7.3503861E-6	m2a	Undefined				
Occupation, traffic area, road network	land	3.4701260E-4	m2a	Undefined				
Occupation, urban, discontinuously built	land	2.1154814E-7	m2a	Undefined				
Occupation, water bodies, artificial	land	1.0807790E-4	m2a	Undefined				
Transformation, from arable	land	1.1890075E-4	m2	Undefined				

11606 items
1 item selected

Figure 30. SimaPro possibility of seeing the input and output

Table 19. MWH life-cycle inventory (embedded phase)

Building elements	Sum of Mass Total (kg)	Acidification (kgSO2eq)	Eutrophication (kgNeq)	Global Warming (kgCO2eq)
Main Building	**66906115**	**116869**	**12455.6**	**30053362**
Ceilings	**1786554**	**6026.283**	**577.1884**	**1666687**
GWB on Mtl. Stud	1786554	6026.283	577.1884	1666687
Curtain Panels	**327660.5**	**3467.388**	**178.5783**	**510930.8**
Curtain Panel: Curtain Panel	76.16628	0.807655	0.040573	115.2714
System Panel: Glazed	317224.4	3363.795	168.9804	480093.1
System Panel: Solid	10359.96	102.7853	9.557376	30722.4
Curtain Wall Mullions	**118439.1**	**1282.076**	**39.88732**	**333950.6**
L Corner Mullion: 5" x 5" Corner	40.95749	0.443355	0.013793	115.4837
Quad Corner Mullion: 5" x 5" Quad Corner	1187.767	12.8573	0.40001	3349.026
Rectangular Mullion: 1.5" x 2.5" rectangular	2559.261	27.70341	0.861895	7216.088
Rectangular Mullion: 2.5" x 5" rectangular	114604.9	1240.571	38.59605	323139.7
V Corner Mullion: 5" V Corner	46.22959	0.500425	0.015569	130.3489
Doors	**354320.5**	**3651.781**	**707.4609**	**1427143**
Curtain Wall Dbl Glass: Curtain Wall Dbl Glass	1057.974	11.27366	0.514721	1926.818
Curtain Wall Sgl Glass: Curtain Wall Sgl Glass	155.6564	1.660357	0.074223	293.5282
Double-Flush: 68" x 80"	7973.69	158.1014	51.65527	88239.92
Double-Flush: 68" x 84"	291.4396	2.531007	0.303059	845.9662
Double-Flush: 72" x 78"	1145.669	9.942465	1.190774	3323.647
Double-Flush: 72" x 82"	451.4873	3.915708	0.469065	1309.135
Double-Flush: 72" x 84"	36599.24	725.6852	237.0977	405021.2
Single-Flush: 30" x 80"	20685.43	188.402	28.43278	63679.75
Single-Flush: 34" x 80"	2493.857	22.4583	3.402729	7593.312
Single-Flush: 34" x 84"	774.9685	6.972811	1.056798	2357.616
Single-Flush: 36" x 80"	109906.9	984.9647	149.4899	333069.5
Single-Flush: 36" x 84"	103751.2	928.9676	141.0355	314141.9
Single-Flush: 42" x 80"	17857.89	158.1042	24.09901	53482.12
Single-Flush: 48" x 80"	51175.04	448.8016	68.63945	151858.4
Floors	**21432691**	**40574.62**	**2608.471**	**8997445**
3" LW Concrete on 2" Metal Deck	562672.1	835.6017	31.00821	191194.7
LW Concrete on Metal Deck	2079188	3126.627	117.232	718273.7
Steel Bar Joist 14" - VCT on Concrete	18790832	36612.39	2460.231	8087977
Roofs	**642378.7**	**6017.787**	**2504.596**	**1275066**
Steel Truss - Insulation on Metal Deck - EPDM	296303.4	1944.707	1655.554	773838.6
Wood Rafter 8" - Asphalt Shingle - Insulated	346075.3	4073.079	849.0413	501227

Structure	**5400506**	**12915.23**	**874.2464**	**3881468**
Footing-Rectangular: 96" x 72" x 18"	2093291	2397.6	85.67017	519377.6
W-Wide Flange: W12X26	1647682	5239.972	392.8753	1675021
W-Wide Flange: W12X26 MWH	19468.31	61.91328	4.642047	19791.34
W-Wide Flange-Column: W10X49	1640064	5215.746	391.0589	1667277
Walls	**36760572**	**41938.07**	**4890.1**	**11821166**
Brick Wall - 8" MWH	87020.9	50.4906	3.488307	24093.82
Exterior - Brick and CMU on MTL. Stud MWH	1153127	1699.454	167.0501	332435.8
Exterior - Brick on CMU 1	6035312	5565.752	633.6504	1825654
Exterior - Brick on CMU 2	351142.6	296.8051	37.71723	86085.11
Exterior - Brick on CMU MWH 1	960304.5	885.5101	100.8185	290468.8
Exterior - Brick on CMU MWH 2	5203352	4798.919	546.3242	1574083
Exterior - CMU on Mtl. Stud MWH 1	203502	492.6862	53.41079	52983.1
Exterior - CMU on Mtl. Stud MWH 2	587743.1	1421.582	154.2421	152404.7
Exterior Glazing	318241	3524.524	250.6352	414139.4
Foundation - 12" Concrete	388309.1	381.5565	19.33143	86811.15
Foundation - 14" Concrete	7171878	7008.558	338.0728	1588231
Interior - 5 1/2" Partition (1-hr)	4508703	5007.927	816.9551	1706168
Interior - 5" Partition (2-hr)	7796917	8621.428	1411.486	2941817
Interior - 6 1/8" Partition (2-hr)	1165930	1289.677	211.0848	440012.4
Interior - 7" Partition (2-hr)	800788.8	883.7139	144.91	301749.4
Masonry - 12" MWH	28299.35	9.489958	0.922878	4030.165
Windows	**82994.09**	**995.808**	**75.06901**	**139506.1**
Fixed: 36" x 72" 1	41961.73	504.7874	38.16587	70822.79
Fixed: 36" x 72" 2	1645.805	19.40376	1.446485	2617.97
Fixed: 36" x 72" 3	461.3094	5.670892	0.4351	827.7682
Fixed: 36" x 72" 4	22112.5	262.8941	19.7145	36061.31
Fixed: 36" x 72" 5	7745.333	90.94198	6.759506	12168.98
Louvers with Trim: Louvers 01	314.8096	7.228251	0.690335	2119.558
Louvers with Trim: Louvers 02	132.5514	3.043474	0.290667	892.4455
Louvers with Trim: Louvers 03	320.3326	7.355063	0.702446	2156.743
Skylight: 20' x 20'	4920.73	55.5507	4.009994	6830.004
Skylight: 44" x 46"	1640.243	18.5169	1.336665	2276.668
Skylight: 6' x 6'	1738.748	20.41555	1.51744	2731.813
Grand Total	**66906115**	**116869**	**12455.6**	**30053362**

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