UTILIZING THE INTERCONNECTIVITY OF MULTI-SECTOR COMMUNITIES FOR INNOVATIVE BUILDING ENERGY EFFICIENCY METHODS

by

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B.S. Civil and Environmental Engineering, Pennsylvania State University, 2006

Submitted to the Graduate Faculty of

Swanson School of Engineering in partial fulfillment

of the requirements for the degree of

Doctor of Philosophy

University of Pittsburgh

2017

UNIVERSITY OF PITTSBURGH

SWANSON SCHOOL OF ENGINEERING

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While each new generation of buildings harness technological advancements in building design and operation, existing generations of buildings must adapt through innovative building efficiency improvement methods. At an annual cost of $380 billion, even minimal incremental improvements can have significant impacts on national energy consumption (U.S. EIA 2017). This dissertation focuses on three communities, students, homeowners, and small commercial stakeholders, each instrumental in building energy curtailment.

The research performed in the student community evaluated: (1) the efficacy of flipped-classroom pedagogy to deliver residential energy content – students' responses to questionnaires indicated increased confidence in knowledge – and (2) student outcomes in two approaches to integrating sustainable engineering to curricula – evaluation of student projects showed increased cognitive thinking in stand-alone sustainable engineering courses over senior design.

In the homeowner community, the propensity of energy audits to stimulate energy investments is ambiguous. The research implemented a survey to evaluate the efficacy of an innovative holistic energy assessment approach to induce energy efficiency improvements. Analysis of survey results indicated homeowners had a more positive perception of motivators for measures adopted versus not adopted (p-value<0.5).

The small commercial community consists of 94% of all commercial building stock with the majority of those buildings smaller than 465 m^2 (5,001 ft^2). A whole building energy disaggregation resource (BEAR) was developed and implemented in thirteen small commercial buildings with 28 tenants to measure accuracy of calculated energy estimations. BEAR was accurate to within 4.7% of electricity bills and 13.3% of natural gas bills in the examined tenants. Moreover, BEAR demonstrated robustness and scalability, design objectives intended for broader implementation across small commercial enterprises. Smart meter data revealed an average error in appliance-level estimation between BEAR and stochastic measurements of 66% for weekdays and 40% for weekends, with uncertainty in estimating appliance parameters driving error. However, improved power or operation data, separately, could reduce these errors by as much as half.

This research employs technical methods in complex environments to identify appropriate methods for disseminating educational materials across the three communities. Results present a larger case for the continued exploration of energy education, in particular through classrooms and energy conservation programs.

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NOMENCLATURE

AAAS	American Association for the Advancement of Science
AASHE	Association for the Advancement of Sustainability in Higher Education
ABET	Accreditation Board for Engineering and Technology
ACEEE	American Council for an Energy-Efficient Economy
AEC	Annual energy consumption
AElC	Annual electricity consumption
AISHE	Auditing Instrument for Sustainability in Higher Education
ANgC	Annual Natural Gas Consumption
AOHr	Annual operating hours
ASCE	American Society of Civil Engineers
ASEE	American Society for Engineering Education
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ASU	Arizona State University
AUHr	Annual usage hours
BEAR	Building energy assessment resource
BEMS	Building energy management systems
BOK	Body of Knowledge 1st edition
BOK2	Body of Knowledge 2nd edition
CAE	Chinese Academy of Engineering

CDD	Cooling degree day (unitless)
CEC	California Energy Commission
CEE	Civil and Environmental Engineering
CSE	Center for Sustainable Engineering
CUCEI	College and University Classroom Environment Inventory
DALY	Daily adjusted life-years
EAC	Engineering Accreditation Commission
EEM	Energy efficiency measure
EEMagg	One of seven aggregated categories of energy efficiency measures
EEMsub	One of twenty one subgroupings of energy efficiency measures
EEMtop	Prioritized list of energy efficiency measures (one through five)
ESD	Engineering and Sustainable Design
ESEM	Earth Systems Engineering and Management
ESP	Energy service provider
EUI	Energy use intensity
GASU	Graphical Assessment of Sustainability in Universities
GC	Grand Challenges
GHG	Greenhouse Gas (emissions)
GREET	Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HDD	Heating degree day (unitless)
HES	Home Energy Saver
HESPro	Home Energy Saver Pro

HVAC	Heating, Ventilation, and Air Conditioning
ICSDEC	International Conference on Sustainable Design, Engineering and Construction
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	Inter-Rater Reliability
kBtu	Thousand British thermal units
kWh	Thousand watt hour
LEED	Leadership in Energy and Environmental Design
NAE	National Academy of Engineering
NELC	National Energy Leadership Corps
NILM	Non-intrusive load monitoring
NSF	National Science Foundation
NTHB	National Trust for Historic Preservation
P_{active}	Modal power demand when in active power operating mode
P_{low}	Modal power demand when in low power operating mode
PNNL	Pacific Northwest National Laboratory
P_{off}	Modal power demand when off
PSU	The Pennsylvania State University
$P_{wt.\ avg}$	Weighted average of all modal power
RAE	Royal Academy of Engineering
RBDC	Residential Building Design and Construction
SBL	Service-based learning
SCB	Small commercial buildings

SHEAR	Sustainability in Higher Education Assessment Rubric
SME	Small and medium enterprises
STAUNCH	Sustainability Tool for Assessing UNiversity’s Curricula Holistically
TUES 2	Transforming Undergraduate Education in Science, Technology, Engineering and Mathematics
UF	Utilization factor
UPitt	The University of Pittsburgh
US DOE	United States Department of Energy
US EIA	United States Energy Information Administration
US EPA	United States Environmental Protection Agency
W	Watt
Wh	Watt hour

ACKNOWLEDGEMENTS

I want to first thank my wife, Rachel, for her unwavering love and unconditional support and patience throughout this journey. She has been an endless guiding light, keeping me focused on the goals I set for myself in this dissertation and in life.

I am also immensely grateful for my adviser Melissa Bilec who's mentoring and leadership provided me encouragement, inspiration, and guidance to shape my passions for life-long learning and empowering communities.

I also want to thank my dissertation committee members for their counsel and encouragement in pursuit of my doctorate. I am appreciative of Vikas Khanna, David Riley, Kristen Parrish, and Leonard Casson.

I want to acknowledge the Green Building Alliance and Pittsburgh 2030 District for their partnership in advancing small commercial building energy research. Additionally, I would like to recognize the Penn State GridSTAR Center and the numerous Pittsburgh community partners, including Kinglsey Association, Rebuilding Together Pittsburgh, Polish Hill Civic Association, and the Pittsburgh Urban Magnet Project for their support in connecting homeowners with student energy leaders.

I also want to acknowledge the Mascaro Center for Sustainable Innovation (MCSI), the National Science Foundation (NSF), the Department of Energy Consortium for Building Energy

Innovation (CBEi), and the BNY Melon Foundation for providing financial support for this research.

To my friends and family, thank you for your patience and support. I look forward to sharing the trail with you again.

1.0 INTRODUCTION

Society faces challenges of increasing complexity as the world's communities become decreasingly isolated, compelling researchers to deliver strategic intercommunal collaborative solutions. Tasked with combatting anthropogenic environmental degradation in the 21st century, efforts have emerged around the problem of energy efficiency in the built environment.

Nationally, buildings represent 40% of annual primary energy consumption at a cost of $338 billion annually (U.S. EIA 2012), while also having been identified as a primary cost effective sector for reducing global greenhouse emissions (Lucon, Ürge-Vorsatz et al. 2014). Contributing 34% of national greenhouse gas emissions (U.S. EPA 2016), U.S. buildings have a measurable impact on climate change. Further, 72% of the U.S. building stock pre-date benchmark building energy and ventilation codes. These buildings must be retrofitted to meet the demands of the future as populations continue to shift to urban centers (U.S. Census Bureau 2012), traditionally where the oldest building stock resides – 84% of the building stock in the Mid Atlantic census division (i.e. New York, NY, Philadelphia, PA, and Pittsburgh, PA) pre-date the benchmark *Energy Policy Act of 1992* (H.R.776 - 102nd Congress 1992, U.S. EIA 2009, U.S. EIA 2012).

Compounding the complexity of building energy efficiency, increased integration of appliances and personal electronic devices to buildings (U.S. EIA 2009, U.S. EIA 2012) has partially offset efficiency gains in heating, ventilation and air conditioning (HVAC) equipment.

Moreover, as HVAC systems become more energy efficient through continued regulatory standards (ASHRAE 2013, S. 535 - 114th Congress 2015), building design and operation becomes more integral to meeting rigorous energy reductions set by the federal government (Gandhi and Brager 2016, Somanader 2016).

Achieving deep and comprehensive building energy reductions requires an integrated approach across multiple communities, decisions makers and sectors, including a workforce with both a sustainable engineering foundation and building energy efficiency expertise. Academic institutions, establishments dedicated to higher education, historically have met the needs of society by continually developing future leaders and policy makers (Lozano, Lozano et al. 2013). To meet the needs of the building sector, academic institutions will need to redefine engineering curriculum to incorporate elements of sustainable development (Zilahy and Huisingh 2009).

Academic institutions have increasingly integrated sustainable engineering to standards and curriculum (ASCE 2008, ABET 2015) as a means to prepare students for careers that will demand systems-level thinking. Sustainable engineering is the balancing of environmental, social, and economic considerations in the design of a product or process. In building science, the product is a building that consumes less energy, and the environmental, economic and social considerations center around energy consumption, e.g. greenhouse gas emissions, costs of energy, and indoor environmental quality.

The research in this dissertation examines three communities: *students*, *homeowners*, and *small commercial stakeholders* (e.g. owners and tenants) under the premise that a multi-pronged and long-term strategy that recognizes the interconnectedness and potential of the communities can catalyze deep building energy reductions. These three communities represent today’s and tomorrow’s building owners, operators, and designers. Prior to outlining the goals and objectives of this dissertation, community interconnectedness concept is described in the following section.

1.1 COMMUNITY INTERCONNECTEDNESS

The overarching aim of this research is to influence long-term building energy efficiency through innovative methods with the premise that education will lead to change (Hirst, Berry et al. 1981, Barr, Gilg et al. 2005, Murphy 2014). The concept presented in Figure 1 depicts the potential for interconnectivity between three communities studied. Included in the figure are the research contributions and mechanisms for delivery of informative building energy efficiency materials.

In the context of this research, a *learning community* is a group of people collectively seeking access to building energy educational materials, or otherwise engaging in energy efficiency, and is considered critical to the achievement of deep energy consumption reductions. People in one community may also reside in another community, e.g. a student may be a homeowner or a homeowner may also be a small commercial building stakeholder.

The concept was developed through four years of experience with the National Energy Leadership Corps (NELC), a program intended to educate students in residential energy efficiency, preparing them to perform holistic home energy assessments, and delivering informative reports to homeowners. Developed at the Pennsylvania State University and implemented at the University of Pittsburgh (UPitt), a total of 120 residential energy assessments have been performed at UPitt. This collective experience of working with students and homeowners, led to the development of the interconnectedness concept presented in Figure 1.

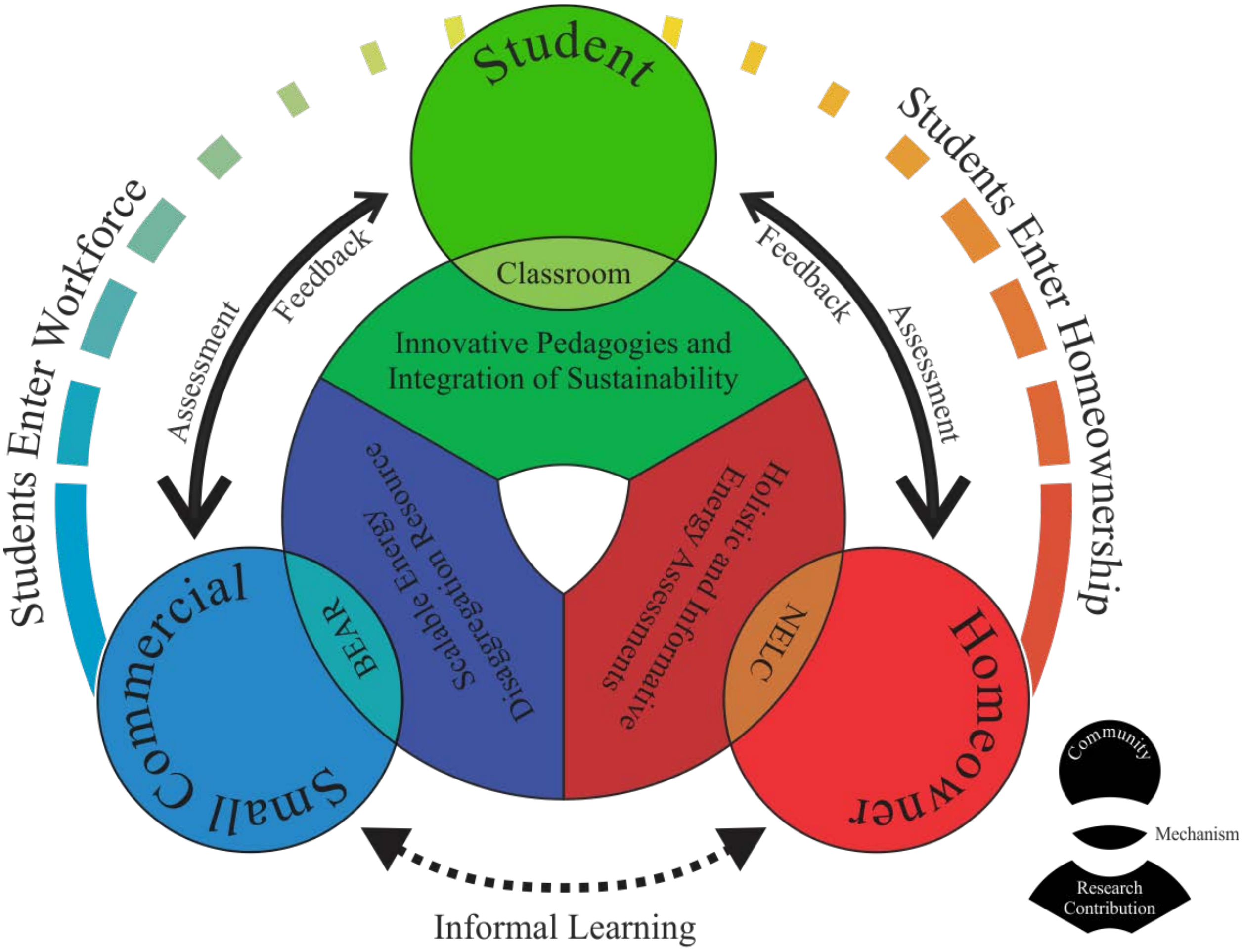


Figure 1. The interconnectivity concept of three communities, *students*, *homeowners* and *small commercial*.

Each community forms a “wedge” built of three formal components: research contribution, mechanism, and community (see bottom right legend in Figure 1). Additionally, informal learning and the temporal elements surround the three community wedges, indicating transfer of information between communities and the shifting of students from *Student* to *Homeowner* and *Small Commercial* communities. Each community is examined.

In the *Student* community wedge, the research contributions include the examination of flipped-classroom pedagogical methods in Chapter 3.0, and evaluation of two approaches to integration of sustainable engineering to existing curricula, a stand-alone sustainable engineering course and senior design, in Chapter 4.0. The mechanism for this examination is the classroom, where students attain a formal education on building energy efficiency through a flipped-classroom, and sustainable engineering through a stand-alone course or senior design course.

In the *Homeowner* wedge, student performed holistic energy assessments are evaluated for the effectiveness to stimulate energy improvement investments in the homeowner group, in Chapter 5.0. The student-performed energy assessments and authored energy reports present the mechanisms from which homeowners receive the informative energy materials.

In the *Small Commercial* wedge, a bottom-up energy disaggregation resource was developed and implemented in thirteen buildings. The developed building energy assessment resource (BEAR) acts as the primary mechanisms for dissemination of information to the small commercial community. In Chapter 6.0, an evaluation of the BEAR is performed to assess the accuracy in estimating whole-building energy consumption and appropriateness for wider use in the small commercial building sector. Chapter **Error! Reference source not found.** expounds on the efficacy of BEAR in estimating appliance-level energy consumption while exploring uncertainty in appliance parameters and generating energy contour plots for the visualization of the relationship between power and operation.

Outside of the formal interaction received through the three studied mechanisms, there are informal transfers of information between learning communities. This informal learning, represented by the black arrows, occurs in two ways: 1) during the student-performed energy assessment and 2) between the homeowner and small commercial communities. During the assessments, students, having become energy leaders through the classroom, communicate energy issues to the building occupants, in turn, occupants provide feedback and other educational information, such as lessons learned in owning a building. Sharing similar building characteristics, small commercial stakeholders are able to apply information learned to their residences, and likewise for homeowners engaged through student-performed energy assessments.

The interconnectedness concept outlined in this section proposes an innovative method for long-term energy reductions through the education of learning communities. These learning communities' relationship with building energy is examined in the subsequent research.

1.2 RESEARCH GOALS AND OBJECTIVES

These three communities holistically represent a larger learning network with the capabilities of decreasing energy use in our built environment. The following research questions were developed from these research communities:

1. *Student*. The initial questions regarding flipped-classroom: (1) *can these engineering education approaches train and foster student learners and energy leaders*, and (2) *does the collected data support the use of the flipped classroom and service learning*, are answered in Chapter 3.0. These approaches are examined in the 2013 American Society for Engineering Education Annual Conference and Exposition conference proceedings (Marks, Ketchman et al. 2014).

While focus on flipped-classroom and service learning pedagogies was initially sought, a greater question evolved as the research progressed. Integration of sustainable engineering into existing civil engineering curricula is important to the continued education of the student community in preparation for 21st century challenges. Two common approaches to integrating sustainable engineering education are the stand-alone sustainable engineering course and integration to senior design. The research questions are, (1b) *how do student outcomes, in the context of sustainability, differ between these approaches, and what do these outcomes suggest for the continued integration of sustainable engineering to curricula*? These are answered in Chapter 4.0.

Table 1. Summary of research question objectives with associated chapter in dissertation.

Learning Community	Chapter	Objectives
Students	3.0	1.1 Evaluate student perceived learning and classroom environment through three implemented evaluative methods 1) pre- and post-module confidence questionnaire, 2) final course reflection journaling, and 3) the College and University Classroom Environment Inventory (CUCEI).
	4.0	1.2 Evaluate course projects for student outcomes, in the context of sustainability, at senior design and stand-alone sustainable engineering courses, using a holistic sustainability rubric, which incorporates cognitive assessment, the quantity and interdependency of sustainability pillars incorporation to projects.
Homeowners	5.0	2.1 Implement a post-energy assessment survey of homeowners with the explicit goal of collecting energy bills and information on implemented energy efficiency measures since their energy assessment.
		2.2 Analyze homeowners' responses to motivation questions using two-sample hypothesis test on the difference in proportions and chi-square test for independence to: (1) identify potential barriers to adoption of classifications of energy efficiency measures and (2) measure if adopted measures are perceived more favorably than non-adopted measures.
Small Commercial	6.0	3.1 Utilizing the residential framework, develop an energy assessment resource that can be used by small commercial building owners or tenants in evaluating their energy use at the building-scale or appliance-scale.
		3.2 Implement the developed resource in a portfolio of buildings to discern the limitations of the resource in different commercial enterprises.
	7.0	3.3 Using the collected building information implement a smart meter study to validate appliance-level estimations while also assessing the magnitude of effect uncertainty has on energy estimation and methods to address.

2. *Homeowner*. Since the overarching aim of this research is reducing building energy consumption, *were the home energy assessments and the proposed energy efficient measures effective in reducing residential energy consumption*?

3. *Small Commercial*. Since small commercial buildings are underserved and follow similarities to residential, *can a robust and technically sound resource, modeled after the residential, be developed to provide meaningful and quantitative recommendations to reduce energy consumption in small commercial buildings*?

To answer the research questions the following objectives, summarized in Table 1, are outlined:

1.1. Evaluate student perceived learning and classroom environment through three implemented evaluative methods 1) pre- and post-module confidence questionnaire, 2) final course reflection journaling, and 3) the College and University Classroom Environment Inventory (CUCEI).

1.2. Evaluate course projects for student outcomes, in the context of sustainability, at senior design and stand-alone sustainable engineering courses, using a holistic sustainability rubric, which incorporates cognitive assessment (Bloom's taxonomy), the quantity and interdependency of sustainability pillars incorporation, and additional metrics (Dancz, Ketchman et al. 2017 accepted).

2.1. Implement a post-energy assessment survey of homeowners with the explicit goal of collecting energy bills and information on implemented energy efficiency measures since their energy assessment. Survey questions include::

  - What energy efficiency measures (EEM) were completed since the assessment?
  - Did the homeowner do the EEMs recommended in the report or did they do others?
  - What is the homeowners' motivation for their decision to adopt or not adopt a recommended energy efficiency measure?

  - Did their energy consumption change since implementation of EEMs according to standardized metrics (e.g. kBtu/HDD)

2.2 Analyze homeowners’ responses to motivation questions using two-sample hypothesis test on the difference in proportions and chi-square test for independence to: (1) identify potential barriers to adoption of classifications of energy efficiency measures and (2) measure if adopted measures are perceived more favorably than non-adopted measures.

3.1 Utilizing the residential framework, develop an energy assessment resource that can be used by small commercial building owners or tenants in evaluating their energy use at the building-scale or appliance-scale.

3.2 Implement the developed resource in a portfolio of buildings to discern the limitations of the resource in different commercial enterprises.

3.3 Using the collected building information implement a smart meter study to validate appliance-level estimations while also assessing the magnitude of effect uncertainty has on energy estimation and methods to address.

1.3 BROADER IMPACTS

The broader impacts of this dissertation are in the development and implementation research aimed at advancing building energy efficiency and sustainable engineering education, and access to meaningful building efficiency information.

The research focusing on the student community assisted the development of the National Energy Leadership Corps course curricula, through which over 100 students were educated and trained in residential energy and energy assessments, and 120 home energy assessments throughout the Pittsburgh, PA community were accomplished. Outcomes of this work provided validation of the effectiveness of the flipped-classroom delivery and service-based learning in teaching holistic systems-thinking principles. Research findings were presented at the 2014 American Society for Engineering Education (ASEE) Annual Conference and Exposition including conference proceedings and at the 2014 Association for the Advancement of Sustainability in Higher Education (AASHE) Conference and Expo in Portland, OR.

Additionally, within the student community, research evaluating student outcomes in the context of sustainable engineering education supports the continuation of academic institutions in integrating sustainable engineering to existing curricula through the stand-alone sustainable engineering course or senior design approach. Findings of the work guide department faculty in decisions on adoption of sustainable engineering to existing curricula in efforts meet accreditation criteria. At a national level, this research offers guidance to the Accreditation Board for Engineering and Technology (ABET) and American Society of Civil Engineers (ASCE) on the incorporation of sustainable engineering student outcomes to accreditation criteria and professional licensure requirements as outlined in the ASCE Body of Knowledge 2nd edition (ASCE 2008, ABET 2015). This research was published in the ASCE Journal of Professional Issues in Engineering Education and Practice (Ketchman, Dancz et al. 2017) and presented in poster form at the 2016 American Association for the Advancement of Science (AAAS) symposium on Envisioning the Future of Undergraduate STEM Education: Research and Practice in Washington, DC.

Within the homeowner community research, students performed 120 individual home energy assessments, which engaged homeowners and provided 600 energy efficiency recommendations through informative and specialized reports with energy consumption implications. Research findings have significant impact to energy conservation program design and implementation, in part suggesting traditional energy audits shift from leveraging primarily financial savings and improved comfort toward a holistic approach of evaluating homeowners' individual priorities and skill sets. Further, findings direct research to expand the traditional list of barriers and motivators, in an exploratory effort to identify rudimentary behavioral indicators for homeowners' propensity to adopt energy efficiency retrofits. Research was presented and published in the conference proceedings at the 2016 International Conference on Sustainable Design, Engineering and Construction (ICSDEC) including conference proceedings, in Tempe, AZ. Further, the research was presented at the 2016 3rd Residential Building Design and Construction (RBDC) Conference in State College, PA. Lastly, a poster was presented at the American Council for an Energy-Efficient Economy (ACEEE) Summer Study on Energy Efficiency in Buildings in Pacific Grove, CA.

The small commercial research developed a bottom-up approach to disaggregating energy consumption scalable to whole building and tenant space applications. The resource embodies a fit-for-purpose design, suitable for use by building owners or tenants. The resource addresses two primary barriers experienced in the small commercial sector by providing an open-source, free to use resource which offers access to meaningful building information, placing more control in the hands of the building stakeholders. The developed resource illuminated needs for collection of higher resolution data in the analysis of modal power and operation as well as identifying employee function, in the context of how an employee uses an appliance. Additionally, this research develops energy contour plots for appliances, which may be used to assist consumer decisions at purchasing of energy efficient appliances by visualizing potential energy consumption patterns. This research was presented at the 2015 and 2017

Engineering Sustainability conferences in Pittsburgh, PA, in addition to a poster at the 2017 International Society for Industrial Ecology (ISIE)-International Symposium on Sustainable Systems and Technology (ISSST) joint conference in Chicago, IL.

1.4 INTELLECTUAL MERIT

The results of this dissertation contribute to the sustainable engineering and building science research communities by advancing the body of knowledge within sustainable engineering student outcomes, pedagogical methods in the context of sustainable engineering, and homeowners' motivations for the adoption of energy efficiency measures.

The primary intellectual contribution of this dissertation is the development of a bottom-up energy quantification resource that assembles disparate scientific tools into a single resource, addressing financial and informational barriers exhibited within the underserved small commercial building sector. Through the integration of publicly available and credible resources in coordination with the advancement of energy algorithms for electricity and natural gas consumption, the developed building energy assessment resource (BEAR) will be made public, enabling future researchers to build upon the bottom-up disaggregation approach. Further, this research has revealed deficiencies in the emerging small commercial research community, primarily in the form of needed support for food service enterprises. The novelty of BEAR is its robustness – it is capable of serving the portfolio of commercial enterprises, including food service which historically is difficult to disaggregate end-use energy profiles. The body of this work has resulted in the publication of two papers which outline the framework of BEAR, and evaluate results of BEAR at the building- and component-scale.

1.5 ORGANIZATION OF DISSERTATION

The organization of this dissertation arises from the three learning communities. A review of literature will be presented to provide context to the research. The subsections will cover background information within each of the three communities. Chapters 3.0 through **Error! Reference source not found.** will present the research performed within each of the three communities, chronicling the development of the intercommunal concept. Chapter 8.0 summarizes the findings of the component research before offering direction for future research looking at sustainable engineering education and building energy efficiency.

2.0 BACKGROUND AND LITERATURE REVIEW

The following sections present literature in alignment of the three communities and associated research contribution. First, the role of sustainable engineering in traditional engineering curricula will be reviewed through three frames of reference: national, departmental, and classroom. To set up the homeowner and small commercial literature, a review of barriers and motivators to energy efficiency adoption will be presented, in the context of both communities. This will be followed by a review of energy audit efficacy in the residential sector. In the small commercial community, energy disaggregation methods and existing building assessment tools are presented, concluding with a review of smart meter studies.

2.1 SUSTAINABLE ENGINEERING IN TRADITIONAL ENGINEERING CURRICULA

Complex sustainable engineering solutions leveraging an interdisciplinary education while balancing the technical skills with the social are needed for engineers to solve challenges posed in the 21st century. In building sciences, students must be capable of identifying, analyzing and conveying high-level technical information on the building design and system operation to an audience commonly lacking a technical background in energy and sustainability. Moreover, building occupants increasingly play a pivotal role in energy consumption as building envelopes and HVAC equipment efficiency improves, meaning occupants' behaviors influence a building's energy profile (Hong and Lin 2013). More than ever, today's engineering curricula must prepare students beyond the technical skills with a holistic education incorporating behavioral sciences in addition to social skills that prepare them to lead from day one.

This section reviews the guiding forces which drive sustainable engineering adoption and integration to curricula by looking from the top-down starting at accreditation and national institutions, which direct the incorporation of sustainability into engineering programs; followed by a review of research examining approaches to integrating sustainability into engineering curricula and evaluative methods. Lastly, this section reviews pedagogical methods for delivering a balance of technical and professional skills to students. The literature presented in this section helped direct the dissertation research to focus on innovative pedagogical methods.

2.1.1 Accreditation and national institutions

Adoption of new curriculum or pedagogical methods in engineering programs are commonly guided through several means, including accreditation boards, the Accreditation Board for Engineering and Technology (ABET), and professional engineering societies, including, but not limited to the American Society of Civil Engineers (ASCE) and National Academy of Engineering (NAE) (ABET 2016, ASCE 2016, NAE 2016). These institutions publish criteria or educational requirements to obtain certification or serve as a steward of research on innovative topics within engineering, ultimately directing at a national level the curriculum that will be implemented at the nation's universities. Recognizing the importance of sustainability in meeting global challenges, these institutes have attempted to address sustainable engineering intended to bring the field of engineering into the 21st century. A review of these institutions roles in developing sustainable engineering curricula follows.

ABET's Engineering Accreditation Commission (EAC) outlines key criteria that are mandatory for each program to fulfill prior to receiving accreditation (ABET 2015). ABET EAC, as of 2016 has 2,131 U.S. 4-year bachelorette degree accredited engineering programs representing 422 universities, including branch campuses, all with international mutual recognition through the Washington Accord (IEA 2016) and other signed mutual recognition agreements (ABET 2016).

ABET's Engineer EAC proposed changes to criteria for the 2017-2018 accreditation period which has significance to sustainability in the field of engineering (ABET 2015). The proposed changes would embed sustainability in the definition of *engineering design* ("*the process of devising a system, component, or process to meet desired needs, specifications, codes, and standards within constraints such as health and safety, cost, ethics, policy,* ***sustainability****, constructability, and manufacturability*"), potentially viewed as a positive step towards engraining sustainability to traditional engineering principles; although, this change ostensibly removed *sustainability* from Criterion 3 Student Outcomes and Criterion 5 Curriculum.

A virtual conference on the proposed changes to ABET's accreditation standards, intended to solicit constructive feedback for the finalization of ABET criterion for the 2017-2018 academic year, was held by the American Society for Engineering Education (ASEE) (ASEE 2016). A review of comments revealed that participants felt that certain key terms, including *sustainability*, were "demoted" from Criterion 3 to the preamble; in doing so suggesting these terms are not required student outcomes (ASEE 2016). Further, commenters suggested and supported the addition of *diversity*, *innovation*, and *a focus on human behavior* as fundamental requirements for engineering education for consideration in Criterion 3. Participants' calls for inclusion of "multidisciplinary project teams" and "professional skill development" language to student outcomes support a holistic education. Through the ASEE virtual conference, participants' comments were recorded for consideration under ABET policy to hold a comment period prior to final adoption of standards. As of the 2017-2018 criteria, the proposed changes *remain a part of the accreditation*, effective 2018-2019.

ASCE is a professional society with members throughout the U.S. and another +24,000 internationally, and is also integral to civil engineering student life through the 288 student chapters and competitive concrete canoe competition (ASCE 2016). In 2004, ASCE convened a committee to develop a Civil Engineering Body of Knowledge for the 21st Century (BOK) establishing prerequisite educational attainment prior to licensure and professional practice (ASCE 2004). The second edition (BOK2) aligns student achievement in each of the twenty four outcomes with Bloom's Taxonomy, presented in Figure 2 (Bloom, Engelhart et al. 1956, ASCE 2008).

Attempts to adopt the ASCE BOK2 student outcomes in combination with ABET criteria have been documented with many suggesting a rigorous process (Gunnink 2010, List 2010, Tocco and Carpenter 2010, Fridley, Hall et al. 2012, Tocco 2014, Brumbelow, Fowler et al. 2015). At the Universities of Alabama, Arkansas and Texas at Tyler (Fridley, Hall et al. 2012) as part of ASCE's *Raise The Bar* initiative (ASCE 2016). The *Raise The Bar* initiative aims to increase educational requirements for professional licensure in order to meet the "*complex challenges facing 21st-century society.*" The universities redesigned the engineering curricula to achieve the twenty-four student outcomes from BOK2 and the eleven (a-k) student outcomes from ABET EAC, including *sustainability*. However, *sustainability* was minimally incorporated into curricula aligning with ABET minimum requirements, suggesting accreditation may have been a driving force for incorporating sustainability curricula.

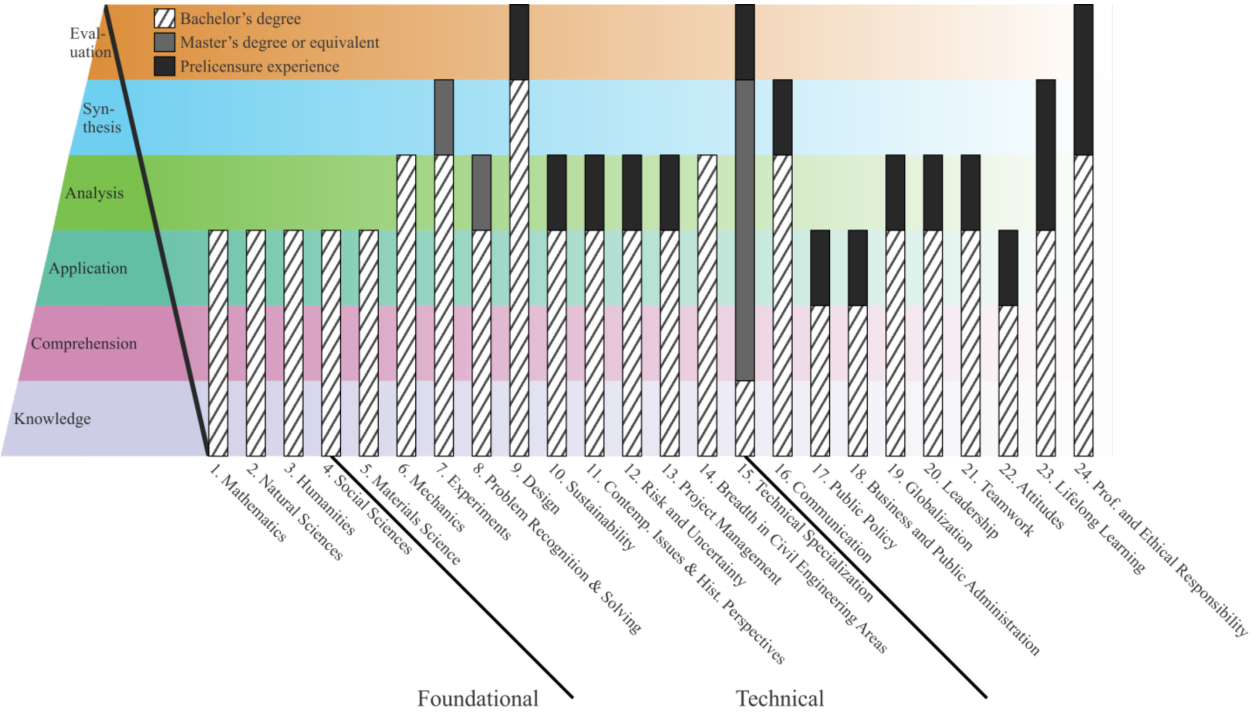


Figure 2. ASCE BOK2 student outcomes with required Bloom's achievement levels and anticpiated achievement timeframe (ASCE 2008). Note: “B” represents achievement through bachelor’s degree, “M/30” represents achievement through the master’s degree or equivalent (30 credit hours of graduate level courses and/or relevant professional practice), and “E” represents prelicensure experience.

Texas A&M University’s undergraduate civil engineering department opted to incorporate BOK2 student outcomes in addition to ABET outcomes, observing that BOK2 is focused toward civil engineers and provides a detail of expectations toward achieving each outcome (Brumbelow, Fowler et al. 2015). Through the redesign process and a survey of recent graduates of the civil engineering program, *sustainability* was identified as an outcome needing further incorporation.

Recently, the conversation surrounding the ASCE Body of Knowledge has looked forward towards the third edition, scheduled for release in 2018, and the continued progress towards holistic educational outcomes (Evans and Beiler 2015). For instance, Evans and Beiler argue that humanities and social sciences should be a focus of the third edition to the BOK, offering three recommendations: (1) raise the minimum Bloom's level of achievement from application (level 3) to analysis (level 4), (2) tie the Foundational outcomes with Technical and Professional in the context of humanities and social sciences, and (3) align the Body of Knowledge with the ASCE Vision 2025 opening statement, which places emphasis on humanities and social science (Evans and Beiler 2015). Further, Evans and Beiler directly connect sustainability with humanities and social sciences, noting that sustainability is founded from the concepts of humanities and social sciences.

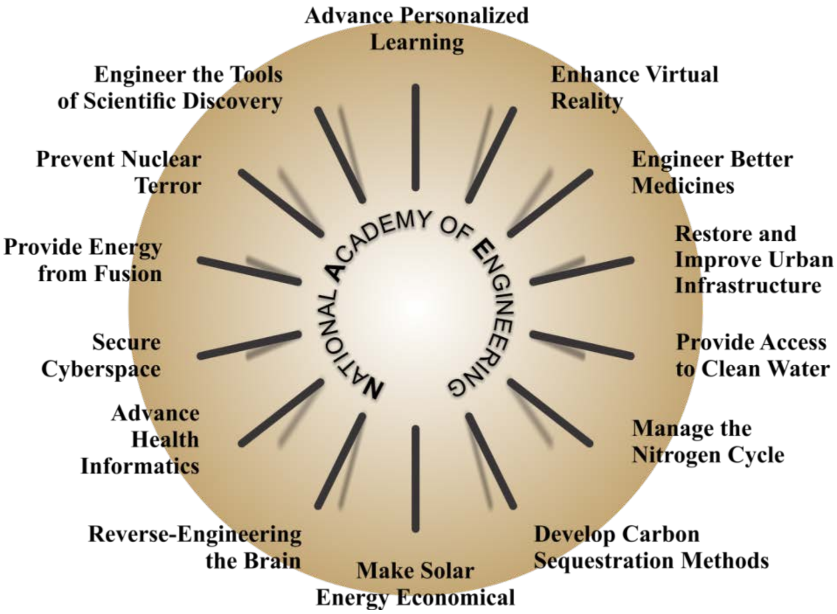


Figure 3. NAE's Grand Challenges for Engineering (NAE 2015).

Conversely, Estes, Lenox et al. (2016) suggest "***lowering the Bloom's threshold***" for outcome *10-Sustainability* in the BOK2, because the "*standard may be too difficult to attain without creating a separate course in sustainability*." The concern of curriculum rigidity and credit hour limitations has arisen as increased demand on the engineering community to adapt to 21st century challenges forces universities to balance traditional and non-traditional educational materials (Chau 2007, Tocco and Carpenter 2010, Barry and Ohland 2012, Fridley, Hall et al. 2012). While important to note here in the context of the Body of Knowledge, this issue is discussed in greater depth in section 2.1.2.

The National Academy of Engineering, which has over 2,000 elected members working in business, academia, and government, in a collaborative effort to "*advance the well-being of the nation by promoting a vibrant engineering profession and by marshalling the expertise and insights of eminent engineers to provide independent advice to the federal government on matters involving engineering and technology* (NAE 2016)." The NAE advises the federal government while conducting independent studies through roughly 900 annually operating National Research Council study committees. In 2008, the NAE released the *Grand Challenges for Engineers* report, which outlined fourteen challenges posing a threat to the sustainment of human existence, illustrated in Figure 3 (Perry, Broers et al. 2008).

Unveiled in March of 2015, 122 U.S. engineering universities signed and presented a letter of commitment to then President Barack Obama, pledging to graduate at least 20 engineers prepared to address grand challenges in engineering through the Grand Challenge (GC) Scholars program (Atkins 2015). The GC Scholars program proposed five components necessary for preparing students, and includes: (1) hands-on project or research experience, (2) interdisciplinary curriculum, (3) entrepreneurship, (4) global dimension, and (5) service learning, illustrated Figure 4. Mote Jr, Dowling et al. (2016), respective Presidents of the US National Academy of Engineering, Royal Academy of Engineering (RAE), and Chinese Academy of Engineering (CAE), offer three positive impacts to global education cultivated from the introduction of grand challenges curriculum.

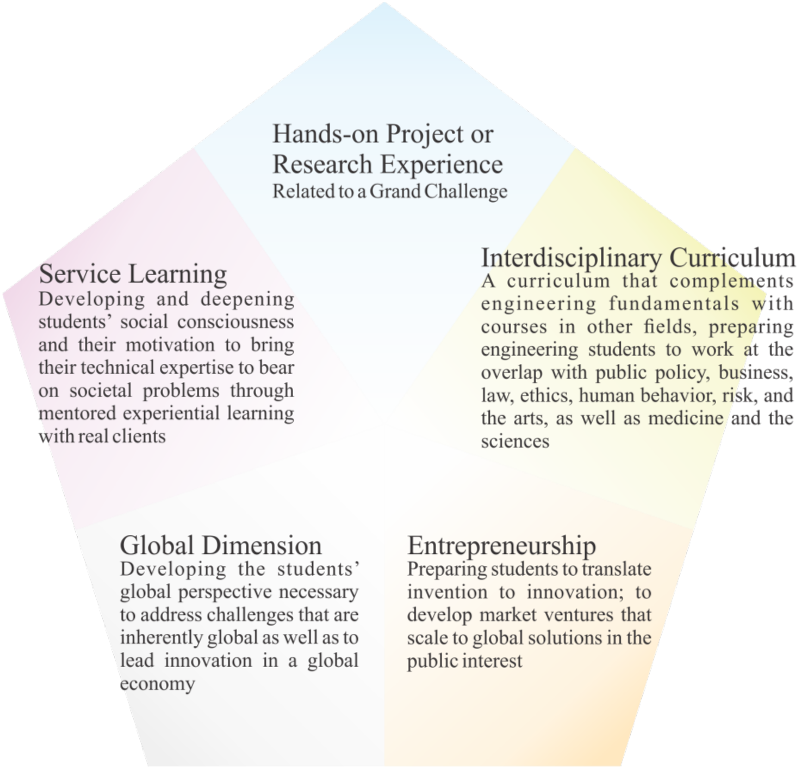


Figure 4. NAE Grand Challenge Scholars program components (Atkins 2015).

First, the GC Scholars program is aiding the transformation of engineering pedagogical methods from traditional lecture-oriented classrooms to a "*hands-on, collaborative, multidisciplinary, problem-solving endeavor*." Second, the GC Scholars program pedagogical approach is effective in attracting underrepresented minorities in engineering, roughly half of the current 160 Grand Challenge Scholars are women, 31 points higher than the 19% average for other undergraduate engineering degrees. Bellingham, Kamal et al. (2016) provide support to the notion that teaching methods influence different demographics differently. Through a survey of 28 students enrolled in a high school robotics course (included NAE Grand Challenge Secure Cyberspace), preliminary results suggest participant desire to continue studying robotics differed by gender, ethnicity and was influenced by teaching method. Lastly, Mote Jr, Dowling et al. (2016) discussed the adoption of grand challenges lessons at the K-12 level, citing the Wake NC State University Early College High School also discussed by Lavelle and Bottomley (2011), among other K-12 schools. At the time of this writing it is only two academic calendar-years removed from the letter of commitment, yet adoption of NAE Grand Challenges to engineering curricula is well-established; although, published quantitative-based research on curricula-integration is sparse.

In particular, Dancz, Plumblee et al. (2016) developed and implemented a rubric to evaluate student competency in the five GC Scholars components. While results of two end-of-semester projects from a stand-alone sustainable engineering course indicate students meet or exceed expectations in the five GC Scholar program components, the rubric demonstrates an initial step towards quantitatively assessing student outcomes.

Prior research from Dancz, Ketchman et al. (2017 accepted) examined students' culminating reports from two universities senior design courses between 2014 and 2015. A total of 43 reports were evaluated for inclusion of NAE Grand Challenges either implicitly, i.e. projects included grand challenges without formally recognizing the NAE Grand Challenges program, or explicitly, i.e. projects directly referenced NAE and the Grand Challenges. Results of the examination revealed a perceived lack of awareness, as no projects explicitly referenced the grand challenges, while only 37% of projects (16 by count) addressed a single grand challenge; 81% (13 of 16 projects) addressed *Restore and Improve Urban Infrastructure*.

The institutions tasked with ensuring academia prepare students for 21st century challenges as they enter the workforce are accreditors, such as ABET, and professional engineering societies, e.g. ASCE. In response to industry demand for engineers with a foundation in sustainability and systems thinking, these institutions have increasingly incorporated sustainable engineering to certification criteria, stimulating universities to follow.

While adoption of sustainable engineering curricula and courses has continually increased, debate over methods for effectively integrating sustainability to existing engineering curricula is debated (Fogarty 1991, Aurandt and Butler 2011, Zhang, Vanasupa et al. 2012, Christ, Heiderscheidt et al. 2015).

2.1.2 Integration of sustainable engineering to curricula

Specialization and prescriptive problem solving common to traditional engineering education lacks the holistic and systems thinking required of complex global challenges (Jonassen, Strobel et al. 2006, Lidgren, Rodhe et al. 2006). Sustainable engineering is proposed as a means to stimulate student cognition transforming perspectives on ecological, social and economic issues (Yona, Bryce et al. 2008). Debate on the *best practices* to integrating sustainable engineering has led to the emergence of three approaches: *module-based* method, *stand-alone* sustainable engineering course method, and integration at *senior design*, illustrated in Figure 5 (Fogarty 1991, Zhang, Vanasupa et al. 2012).

The *module-based* method integrates individual lessons, or modules, to existing course curricula, providing interdisciplinary educational materials intended to achieve higher levels of cognition and spur student interest in sustainability (Bielefeldt 2011, Watson, Lozano et al. 2013, Oswald Beiler and Evans 2015). Research has suggested positive student outcomes. When used in first-year courses it may stoke students' interest in sustainability and continued use in other course assignments, even when unsolicited, as observed by Bielefeldt (2011). Watson, Lozano et al. (2013) conclude that weaving sustainability throughout existing technical engineering courses promotes a holistic perception of sustainability and may encourage continued use, also theorized by Peet, Mulder et al. (2004); although no longitudinal studies have been performed to confirm.

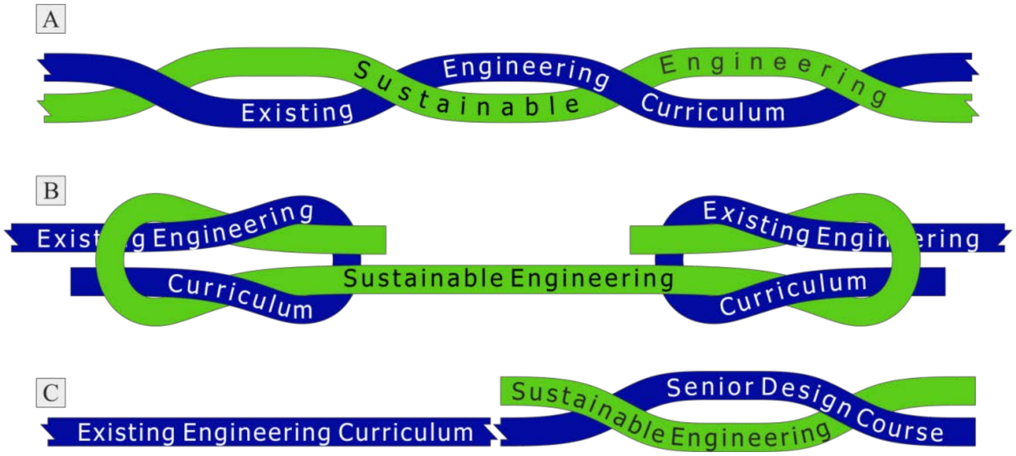


Figure 5. The three emergent methods for integrating sustainable engineering, A: Module method - sustainable engineering woven throughout existing traditional engineering courses; B: Stand-alone method – distinct sustainable engineering courses inserted between existing curriculum; C: Integration to senior design – sustainable engineering module(s) inserted to the senior design course and engineering design project.

However, obstacles exist which make the module-based method less desirable than others. As Ceulemans and De Prins (2010) stated, the module-approach, or horizontal integration, is reliant on course instructors. From a departmental perspective, the module-based method requires more instructors to participate than in the stand-alone approach, thereby requiring instructors to participate in educational workshops. This may lead to resistance by some faculty; although Brown, Bornasal et al. (2015) suggest targeted integration to overcome this barrier. Further, research has discussed organizational inhibitors to adoption of sustainability, including but not limited to: tradition and convention, divided disciplines, and faculty promotion structure, i.e. low priority to community engagement and emphasis on journal publication (Peet, Mulder et al. 2004, Stephens, Hernandez et al. 2008, Bacon, Mulvaney et al. 2011, Sylvestre, Wright et al. 2013). While faculty and organizational barriers are present under either integration method, these may be more prevalent in module-based approaches when necessary to engage more faculty and department leaders.

In the *stand-alone* approach, or vertical integration, a university may adopt one or more courses on sustainable engineering, minimizing department and faculty involvement, contrary to the module-based method (Ceulemans and De Prins 2010). Benefits of stand-alone sustainability courses to student outcomes have been discussed, including: deeper exploration to the principles of sustainability (Stubbs and Cocklin 2008, Hegarty, Thomas et al. 2011) and transdisciplinary experiences in design courses (Boks and Diehl 2006). Ceulemans and De Prins (2010) noted instructors desire to employ stand-alone sustainable engineering courses in an introductory trial period, in lieu of a comprehensive restructuring of curriculum; a possibility for lessening the institutional burden of having to reformulate curriculum at all levels. Additionally, researchers have suggested that incorporation of sustainability to courses outside engineering, or opening sustainable engineering courses to cross-disciplinary students, would indorse student awareness of ecological and societal issues (Peet, Mulder et al. 2004, Lozano 2010, Watson, Lozano et al. 2013), including at the K-12 level (Oswald Beiler and Evans 2015).

While having dedicated courses on sustainability promotes depth and exploration of sustainability in engineering, researchers have noted that autonomous sustainable engineering courses may endorse compartmentalization of sustainability (Peet, Mulder et al. 2004, Lidgren, Rodhe et al. 2006). In a sense, stand-alone integration perpetuates the failures of “divided disciplines” when attempting to teach transdisciplinary lessons (Stephens, Hernandez et al. 2008). Moreover, Hegarty, Thomas et al. (2011) note that students may resist the adoption of sustainability curricula, especially in universities where sustainable engineering courses are required, further complicating integration of stand-alone courses.

In *senior design*, also referred to as capstone design, sustainability integration echoes the module-based method; although the semester-long culminating design project incorporates sustainable engineering design criteria (Watson, Pelkey et al. 2016). ABET accreditation, which requires students complete a culminating *engineering design* experience, includes sustainability in the definition of engineering design (ABET 2015). Moreover, the ASCE BOK2 also defines a Bloom’s level of achievement, “application,” for sustainability prior to graduation with a bachelor’s degree in civil engineering (ASCE 2008). While applying a module-style approach, senior design integration of sustainable engineering stands apart from module-based methods through its comprehensive culminating engineering design project. Research looking at senior design integration of sustainability tends to focus on these metrics (Pierrakos, Barrella et al. 2013, Jiji, Schonfeld et al. 2015, Yuan, Fraser et al. 2015).

Consensus points at senior design as an opportune time for students to experience real-world constraints while flexing the technical and professional skills learned through their collegiate careers. However, if sustainability was not integrated prior to senior design, students may not be receptive to adopting sustainable engineering design that late in their collegiate career (Yuan, Fraser et al. 2015). At the Georgia Institute of Technology, students are required to take at minimum a sustainability introductory course (Watson, Barrella et al. 2013). Analysis of senior design projects’ content revealed that students incorporated all three pillars of sustainability; social aspects were incorporated more extensively than others. Watson, Barrella et al. (2013) offer that instructor and project sponsor acted as the primary driver for project content, also presented in (Boks and Diehl 2006).

With the integration of sustainable engineering curricula to course syllabi, students learning of material partially forms around the pedagogical method implemented in a course. The following section reviews research performed on two pedagogies, flipped-classroom and service-based learning.

2.1.3 Pedagogies for sustainability

Two innovative pedagogical approaches are the flipped-classroom and service based learning. In the flipped-classroom, the traditional approach of lecturing in the classroom and assigning course work to be completed at home are reversed. In service based learning (SBL), students are introduced to the community in which they reside through community projects. This review will summarize the benefits and deficits of traditional classrooms, flipped-classroom, and the service-based learning approach. A comprehensive review of traditional and flipped-classroom pedagogies is presented in Chapter 3.0.

Traditional pedagogical approaches perform an important task of disseminating volumes of educational material to students in the limited time available (i.e. one semester in stand-alone courses or one class period in module-based approaches). However, research has noted that student retention of information, ability to analyze and apply the learned knowledge may suffer in traditional course (Mills and Treagust 2003, Sams and Bergmann 2013). Causality has been suggested to stem from a limited teacher-student interaction, rigid pace of lectures, and application of a single information delivery method (Toto and Nguyen 2009, Goodwin and

Miller 2013). In the engineering curriculum, a strong emphasis on learning through application can be beneficial to students by developing competencies valuable in the workforce as well as encouraging traditionally underrepresented minorities in engineering to enroll (Mills and Treagust 2003, Lockrey and Bissett Johnson 2013, Leal Filho, Shiel et al. 2016, Mote Jr, Dowling et al. 2016).

Flipped-classroom design employs learning through application by having students interact with instructors and one another through educational discussions. Unlike traditional lectures, flipped-classroom aims to promote student-teacher interaction and problem solving and while fostering professional skills in students (e.g. communication, leadership, and decision making) (Zappe, Leicht et al. 2009). Conversely, while traditional pedagogical approaches succeed in disseminating information to large audiences in short periods, flipped-classroom design struggles due to the demand on teacher-student interaction (Lage, Platt et al. 2000, Brunsell and Horejsi 2013). Other potential struggles noted by Cavalli, Neubert et al. (2014) include getting students to watch video lectures outside of class and instructors confidence with the teaching method, potentially leading to the results that students did not benefit from the flipped classrooms examined in their study.

Service-based learning engages students and the communities in which they live. Defined as the integration of community service and academics with the purpose of strengthening the community and fostering civic responsibility within students, service-based learning has been shown to have a positive influence on student outcomes (A. Astin, L. Vogelgesang et al. 2000, Carter 2011, Lemons, Swan et al. 2011). It has been observed that students participating in SBL courses demonstrated more adaptive self-regulation strategies than those students enrolled in more traditional courses (Galand, Raucent et al. 2010, Lemons, Swan et al. 2011). Moreover, studies have reported increases to student satisfaction measured through student evaluations and reflective journaling (Dutta and Haubold 2007, Dukhan, Schumack et al. 2008, Goggins 2012). Dutta and Haubold (2007) also showed an increase interest in the students' intended field of study and subsequently lower transfer/drop-out rates over their three-year study. Dukhan, Schumack et al. (2008) attempted to quantify student outcomes illustrating negative, neutral, and positive indicators taken from reflective journals. The results showed increased positive indicators during and after the SBL activity owing to heightened apprehension leading up to the activity. Goggins (2012) results pointed towards student ownership of their learning and increased motivation in students when learning is not "just to get marks to pass the exam."

Integration of sustainability to engineering curricula is pivotal to preparing students to address complex multidimensional problems. Academic institutions understand the importance of a multidisciplinary education and have increasingly incorporated sustainability, which embodies holistic thinking to balance the three pillars, ecological, societal, and economic. Not only representing the future of building engineers and designers, students will also become homeowners and employed in commercial buildings, connecting students more closely with these communities over time.

As students' graduate to homeownership and enter the workforce they will bring with them the knowledge obtained through their collegiate careers. Transitioning from the student community to homeowner and potentially small commercial communities, they will face new challenges of sustainable engineering. This dissertation examined methods for educating homeowners and small commercial stakeholders using innovative methods. The following sections will review pertinent literature that assisted the development of research questions, including the barrier-motivator nexus, energy audits, and energy quantification methods.

2.2 BUILDING ENERGY EFFICIENCY: BARRIER-MOTIVATOR NEXUS

In buildings, stakeholders (e.g. owner or occupants) must voluntarily choose to implement energy efficiency measures. Their decision for choosing or not choosing to implement an energy efficiency measure (EEM) is influenced by barriers and motivators. In this dissertation, research was conducted in residential and commercial buildings aimed at stimulating energy investments through educational methods, such as a holistic energy assessment or informative energy disaggregation resource. The barriers and motivators described in this section assisted the formulation of the research questions and experimental design employed in this dissertation.

Table 2. A list of commonly experienced barriers based on the taxonomy presented by Sorrell, Schleich et al. (2000) and compiled in (Trianni and Cagno 2012).

Economic, Non-Market Failure	Economic, Market Failure	Behavioral	Organizational
Access to capital	Fragmentation	Bounded rationality	Culture
Heterogeneity	Imperfect information	Credibility and trust	Energy manager lacks influence
Hidden costs	Lack of information	Form of Information	Lack of sub-metering
Risk aversion	Principal-agent relationship	Inertia	
	Split incentive	Resistance to change	
		Values	

Barriers are defined as "*obstacles to the efficient use of energy*" (Weber 1997) and have been studied extensively for their influence on the residential and commercial communities (Rohdin and Thollander 2006, Schleich and Gruber 2008, Fleiter, Schleich et al. 2012, Trianni and Cagno 2012, Kostka, Moslener et al. 2013, Murphy 2014). Homeowners and commercial building stakeholders (defined as the building owner and tenants) experience different barriers at different degrees, and may change over time. To stimulate investments in energy efficient technologies, energy audits must be attuned to their customers' individualized prioritized list of barriers, and motivators, considered the *barrier-motivator nexus*.

Many barriers leading to the energy-efficiency gap, the difference in actual and potential energy efficiency investments by building owners (Hirst and Brown 1990), have been postulated and investigated. A summary of the barriers is synthesized in Table 2. *Lack of information* is considered central to building energy efficiency investments. Research has presented evidence that energy audits could overcome these barriers (Jaffe and Stavins 1994, Sorrell, Schleich et al. 2000, Frondel and Vance 2013). Theoretically, the energy audit provides building owners with information on energy efficiency measures, energy savings, and the building energy profile creating a better-informed owner leading to energy efficiency investments (Gruber, Fleiter et al. 2011, Murphy 2014). In the small commercial building sector exhibits strong financial barriers, focusing on upfront costs of energy efficient technologies and costs of obtaining information (Fleiter, Schleich et al. 2012, Trianni and Cagno 2012, Kostka, Moslener et al. 2013). A recent study found *high up-front investment requirement, lack of government policies to support energy efficiency improvements, higher cost of capital, and lack of information and awareness are the most critical barriers to the improvement of energy efficiency in the industrial and commercial sectors in Ukraine* (Timilsina, Hochman et al. 2016).

Motivators may be defined as *incentives to the efficient use of energy*; although, motivators are not the opposite barriers. For example, having access to capital is not a motivation for investing in energy efficiency, unless the capital is restricted, typically through government or an energy service provider, to application in energy efficient investments. As noted by Kontokosta (2016), drivers to energy efficiency adoption has not been widely studied in commercial or residential, especially in the small commercial realm, inhibiting a well-defined list of motivators as was performed by Sorrell, Schleich et al. (2000) for barriers. However, in an effort to develop a taxonomy of motivators, studies have explored a wider breadth of drivers to the adoption of energy efficient technologies and practices (Rohdin and Thollander 2006, Pellegrini-Masini and Leishman 2011, Popescu, Bienert et al. 2012, Cagno and Trianni 2013, Persson and Grönkvist 2015). A brief summary depicting the breadth of research across building sectors is presented in Table 3.

As is demonstrated in the following section 2.3 “Residential Community” it is imperative to balance the barrier-motivator nexus to successfully engage homeowners in energy efficiency. Although not discussed in this research, the small commercial building sector also benefits from balancing barriers and motivators. When developing energy conservation tools or programs, it is important to consider the barriers and motivators that may be present in the target audience (Fuller, Kunkel et al. 2010). Therefore, it was important to review before discussing the residential and small commercial communities.

Table 3. A summary of motivators identified through a review of research (Gram-Hanssen, Bartiaux et al. 2007, Kontokosta 2016, Kuppig, Cook et al. 2016, Wang, Li et al. 2016).

Taxonomy adapted from Kuppig, Cook et al. (2016)	Identified Motivators to Adoption	Authors	Sector
Financial	Saving on operational energy costs	Wang, Li et al. 2016	Health care
Financial	Attracting high-quality professionals		
Compliance	Building reputation with the government		
Health/Compliance	Obtaining financial reward from the government		
Health/Compliance	Improving medical environment of hospitals		
Health/Compliance	Adapting to development trends		
Health/Compliance	Following the requirements of laws and regulations		
Social	Improving public image healthcare and hospitals		
Environment	Energy efficiency	Kuppig, Cook et al. 2016	University
Environment/Health	Reduced environmental and health risk		
Financial	Acceptable payback		
Financial	Reduced operating cost		
Financial	Reduced business risk		
Financial	Increased employee productivity		
Health/Compliance	Health and safety benefits		
Health/Compliance	Regulatory compliance		
Health/Compliance	Other companies implemented		
Social	Corporate commitment		
Social	Enhanced environmental awareness		
Social	Improved public image		
Environment	Environmental benefits	Kontokosta 2016	Commercial
Financial	Reduced energy bills		
Financial	Attractive returns		
Financial	Take advantage of incentive		
Financial	Lower operating costs, competitive rent		
Financial	Increase tenant comfort		
Financial	Efficiency, higher rents		
Health/Compliance	Repairs		
Social	Increase marketability		
Social	Market recognition		
Social	Peer influence		
Information	Aligned recommendations with homeowner identity	Gram-Hanssen, Bartiaux et al. 2007	Residential
Information/Social	Others have implemented		
Priority	Time pressure		
Social	Aesthetics		
Social	Comfort and convenience		

2.3 RESIDENTIAL COMMUNITY

At over $180 billion annually, single-family homes account for 80% of residential sector primary energy consumption, or roughly one sixth of national (U.S. EIA 2009). Moreover, the estimated 78 million single-family housing units nationally represent 70% of all buildings. The importance of addressing the residential sector building energy efficiency in an effort to curtail greenhouse gas emissions is evident (Lucon, Ürge-Vorsatz et al. 2014). Energy audits have been theorized to provide the necessary information and guidance to homeowners, overcoming the energy efficiency paradox (Jaffe and Stavins 1994, Frondel and Vance 2013, Palmer, Walls et al. 2013).

This section will review the efficacy of energy audits to stimulate energy improvements in the residential sector and how energy audits are shifting from financial to holistic energy improvement recommendations, briefly reviewing the National Energy Leadership Corps as an example of holistic energy assessment design (Chapter 5.0).

2.3.1 Energy audit efficacy

The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) defines three tiers of energy audits (ASHRAE 2011). A Level I audit applies a simplistic approach of visual inspection, review of energy bills, and brief interviews with building managers, basing energy recommendations from this collection of information. A Level II energy audit collects field data, including energy bills and qualitative information through discussions with occupants, and performs an energy bill analysis. At the highest level of energy audits, Level III, auditors perform rigorous field data collection and post-audit analysis, e.g. blower door test and whole building modeling. Although energy audits provide information on energy conservation strategies, the industry has focused on financial savings disregarding homeowners' holistic indicators (e.g. thermal comfort, priority, or environmental responsibility) choosing to market recommendations primarily based on financial savings (Fuller, Kunkel et al. 2010, Ingle, Moezzi et al. 2012). This has in part led to the observed ineffectiveness of energy audits in stimulating energy investments; see Table 4 for a review of 11 energy conservation programs (Fuller, Kunkel et al. 2010).

While audits have long been recognized as a method for disseminating information to homeowners on their home energy profile, investments in energy upgrades do not reflect this (McDougall, Claxton et al. 1982, Hirst and Goeltz 1985, M.C. Fuller, C. Kunkel et al. 2010). Palmer, Walls et al. (2013) surveyed 479 energy service providers (ESP) across the U.S. to explore how audit information is provided to homeowners, and how homeowners use this information. Their conclusions suggest that the majority of homeowners are unaware of what an energy audit provides and the costs associated act as a significant barrier to purchasing an audit. Palmer, Walls et al. (2013) postulate that envelop improvements are harder for homeowners to conceptualize, making them less likely to be completed; although participating ESPs indicated that envelop improvements were a primary recommendation to homeowners. *Consequently, an estimated 30% of homeowners receiving an audit made no investments post-audit*. A national survey of homeowners in the Netherlands observed similar low adoption rates; 19% of audit recipients invested in energy retrofits, estimating between 60% and 70% of energy retrofit recommendations were ignored (Murphy 2014). Low investment rates were also seen in studies concluding energy audits had little to no effect (McDougall, Claxton et al. 1982), while subsidies had a little influence on adoption rates (Hirst and Goeltz 1985).

Table 4. Summary list of residential energy efficiency programs from Driving Demand for Home Energy Improvements for those reporting adoption rates (Fuller, Kunkel et al. 2010).

Program Name	Program Location	# of Upgrades Completed; % of Homes Assessed*
Bonneville Power Administration (BPA) Weatherization Programs	Pacific NW	~900,000 homes upgraded; ~60% of homes assessed did an upgrade during the BPA Interim Program
Energy Smackdown	Massachusetts	All 100 homes in pilot made some improvements
Hood River Conservation Project (HCRP)	Hood River, OR	2,989 homes upgraded; 91% of home assessed
Houston's Residential Energy Efficiency Program (REEP)	Houston, TX	8,400 homes upgraded
Jasper Energy Efficiency Project (JEEP)	Jasper, Canada	891 homes upgraded to some degree
Keystone Home Energy Loan (HELP)	Pennsylvania	5,500 loans; about 10% of these for comprehensive home energy improvements
Long Island Green Homes (LIGH)	Babylon, NY	366 homes upgraded; ~70% of homes assessed
Marshfield Energy Challenge	Marshfield, MA	280 homes upgraded to some degree; ~22% of homes assessed
NYSERDA's Home Performance with ENERGY STAR Program	New York	33,000 homes upgraded
Vermont Community Energy Mobilization (VCEM) Project	Vermont	~2% of the 576 single family homes visited have done more comprehensive work
WeatherizeDC	Washington, DC	20 homes upgraded; 27% of homes assessed

A study conducted by Ingle, Moezzi et al. (2012) surveyed 286 households in Seattle, Washington who received an energy audit through the Seattle City Light program to analyze the state-of-the-practice of energy audits and to determine shortcomings. Survey results showed that while homeowners indicated financial savings was a primary determinant in choosing a retrofit to invest, *comfort was a more prominent factor*. Similarly, Murphy (2014) explains that homeowners make decisions on energy retrofits more so on comfort, and *not the technical* *information* provided through an energy audit, adding that homeowners knowingly incur higher energy bills in order to maintain a level of comfort deemed cost worthy.

Frondel and Vance (2013) proposed the influence of energy audits on homeowner investments was inconclusive having recorded ambiguous results from the 2,530 homes a part of the 2005 German Residential Energy Consumption Survey. They found that optimistic audit recipients were sometimes discouraged by audit results if savings were not as anticipated, and conversely for pessimistic recipients; higher than anticipated savings potential increased likelihood to invest in energy upgrades. Metcalf and Hassett (1999) examined the engineered return rates on investment against realized returns to determine the extent of the *energy paradox*, i.e. when cost effective energy efficient technologies are available to customers but are not adopted (Jaffe and Stavins 1994). Metcalf and Hassett (1999) found realized return rates within 5% of the engineered rates, concluding that the engineered and realized return rates are “not dissimilar enough” to prevent homeowners from investing in energy retrofits, demonstrating the energy paradox persists even today. In general, research suggests energy audits have been ineffective in stimulating energy efficiency investments in the residential community (Ingle, Moezzi et al. 2012, Palmer, Walls et al. 2013, Murphy 2014).

However, participant sampling bias in residential energy audit studies has been identified as potentially problematic when reporting audit efficacy. Abrahamse, Steg et al. (2005) postulated that small sample sizes collected in some research inhibit pattern recognition, leading to negative conclusions on the efficacy of energy audits. Murphy (2014) pointed out the bias of energy audit participants; typically from higher income and higher educated households respective to their location. Hirst, Berry et al. (1981) noted an increased interest in energy conservation in the energy audit recipient population over the general population. Bruel and

Hoekstra (2005) observed that poorer populations were motivated by subsidies to energy audits and retrofits, while wealthier populations responded to recommendations for improved comfort and societal responsibilities. Other papers found similar socio-economic indicators in age of residents, housing type and income were linked to energy use (Barr, Gilg et al. 2005, Martinsson, Lundqvist et al. 2011). Because energy audit programs are either voluntary or purchased by recipients, and may be regionally located, sampling bias is inherent to results, and should be considered prior to reporting results of audit efficacy.

Heterogeneity of the residential sector and the lackluster performance of traditional energy audits have led to increased calls for holistic energy audit and program design (Fuller, Kunkel et al. 2010, Ingle, Moezzi et al. 2012, Revell 2014). The National Energy Leadership Corps (NELC) represents one effort to foster market transformation through educating the next generation of energy auditors in holistic energy assessment methods, while supporting research to explore the extent homeowner behavioral indicators correlate to investment in energy retrofits.

The NELC, a program developed by Pennsylvania State University and piloted at the University of Pittsburgh, is intended to teach students about home energy efficiency and sustainability, empowering them to conduct home energy assessments in their community. The design of the program reflects the need for alternative models to personally engage homeowners in a holistic approach to home energy and sustainability concepts, intended as a response to the limitations of traditional professional home energy audits. Addressing the barrier-motivator nexus in the homeowner community, the NELC went beyond financial motivators by also engaging homeowners' world views and interests (Riley, Whelton et al. 2012). The multifaceted program begins in the classroom where students are first taught about energy assessments and the home as a system in a flipped-classroom education model. The students are provided hands-on training in the performance of in-home energy assessments culminating with a student-authored personalized educational report to homeowners on their home's energy profile and ways to improve efficiency, safety, and health.

Employing the NELC holistic energy assessment model to small commercial was the next developmental step in this dissertation. Small commercial buildings contain similar mechanical equipment, e.g. furnaces and hot water heater tanks, and small commercial building occupants that are also homeowners. It was logical to attempt to reframe the holistic energy assessment approach to small commercial. However, limitations arose from a lack of accessible energy quantification resources and building heterogeneity, leading to the development of a building energy assessment resource (BEAR).

2.4 SMALL COMMERCIAL BUILDING ENERGY DISAGGREGATION

In the commercial sector, 94% of all commercial buildings are considered small (<50,000 ft^2 in floor area), and house over 90% of all small and medium commercial enterprises (enterprises with less than 100 employees) (U.S. EIA 2012). Constituting roughly 9% of national primary energy consumption, small commercial buildings represent a critical component to energy reduction strategies. However, building heterogeneity and barriers to energy efficiency investments experienced by building tenants inhibit generalization of building energy investments, such as incentive programs. An initial step towards the next generation of energy reduction strategies is development of a disaggregation model, which would provide building owners and tenants a higher resolution of energy use in their building or space. The following section reviews the state of energy quantification methods and fit-for-purpose thinking in commercial buildings, looking briefly at computational methods followed by measurement-based approaches, which are applied to this research. Lastly, this section reviews existing energy assessment tools performing energy disaggregation.

2.4.1 Energy quantification methods and fit-for-purpose thinking

While medium and large commercial buildings benefit from homogeneous building design and operation, the small commercial building sector suffers extreme heterogeneity, inhibiting “one-size-fits-all” energy retrofits applicable to medium and large buildings, see Figure 6. Therefore, small commercial building stakeholders must review their individual energy use prior to making energy improvements. Energy bills provide a very low resolution of energy use, i.e. monthly consumption with recorded heating or cooling degree days (not specific to the building’s HVAC operation); yet, this is the primary interaction between building stakeholders and their measured energy consumption. Several methods are available to small commercial building stakeholders to derive an energy profile, and fall under two categories: calculation-based and measurement-based.

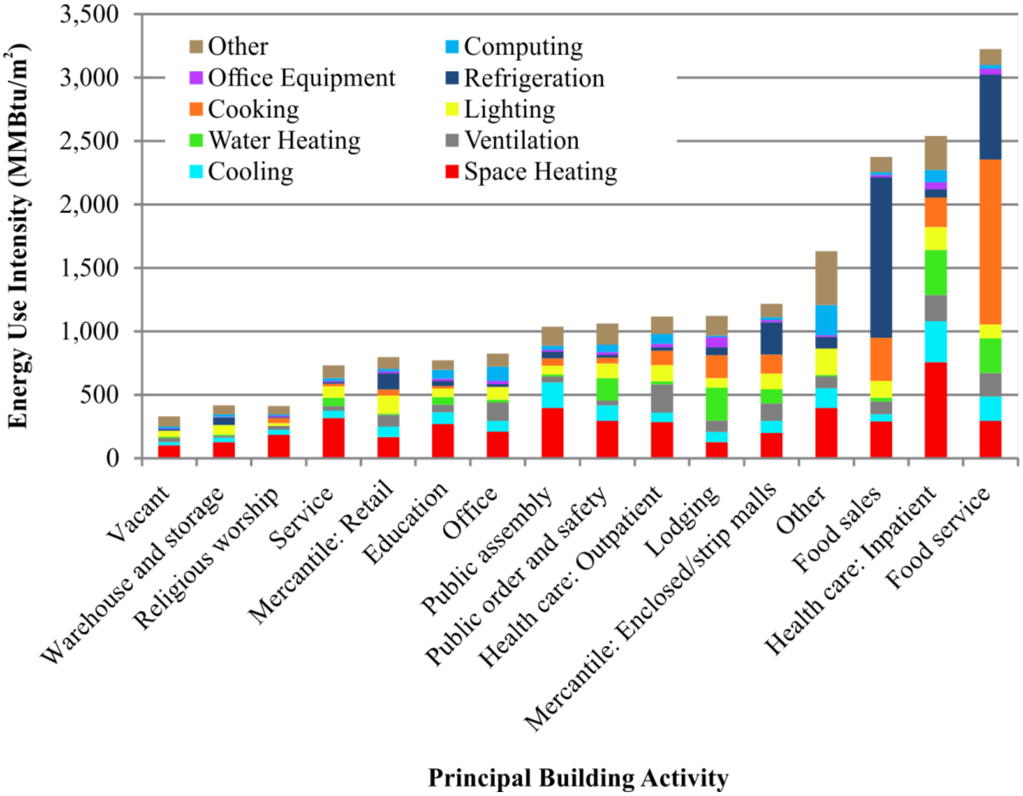


Figure 6. Energy use intensities (EUI) organized by end-use and principle building activity (U.S. EIA 2012).

Fit-for-purpose can be defined as *something good enough to do the job it was designed to do* (Gaetani, Hoes et al. 2016). In terms of energy quantification, comprehensive energy simulation packages require complex information beyond the scope of SCB owners' and tenants' needs, while disaggregation employs easily accessible and readily understood energy data or observational information. Transparency, robustness, and reproducibility, desired in regulatory building efficiency computations are important mechanisms of building performance quantification (van Dijk, Spiekman et al. 2005). Gaetani, Hoes et al. (2016) present a decision tree framework directed towards engineers and policy makers when developing energy efficiency programs to ask: (1) WHAT is the scale of the program (i.e. single building to regional building stock, (2) WHY do we want building energy information (i.e. hot-spot analysis or continuous real-time performance indicators), and (3) WHEN in the life-cycle phase are we evaluating (i.e. design or operation). Discussed in the context of simulation software, the fit-for-purpose model is also appropriate for small commercial building stakeholders, who may operate in a single space, only requiring a hot-spot analysis, or as a portfolio manager with multiple buildings over several geographic regions, intent on upgrading the building portfolio energy performance. Over the next sections, fit-for-purpose thinking reveals the benefits of measurement-based quantification over calculation-based in the current state of building energy research and practice, in the context of small commercial buildings.

2.4.2 Calculation-based methods

Calculation- based approaches methods are most commonly recognized through use in building energy modeling software, such as EnergyPlus, and are widely used in design and research (Crawley, Lawrie et al. 2001, Kubba 2015, Harish and Kumar 2016). Calculation-based methods include dynamic and steady-state modeling, which use software programs to simulate building energy profiles while applying building parameters, including but not limited to: orientation, mechanical system characteristics, and dynamic operation parameters, to determine end-use energy consumption. Steady-state models offer the users a quick modeling method, leveraging a small number of inputs with transparent calculations resulting in reproducible energy profiles (Kim, Yoon et al. 2013). In addition, Kim, Yoon et al. (2013) note that steady-state models are intuitive and correlations between inputs and outputs can be made. Dynamic simulations are capable of a higher level of modeling and can account for the complex systems not suited for steady state models, such as daylighting and energy management systems (Crawley, Hand et al. 2008).

However, while calculation- based approaches methods have their merits in larger commercial buildings or portfolios, many small commercial building owners and their SME tenants cannot use these methods because they often suffer systemic inhibitors, including: access to capital to pay for energy models, knowledge or skills to conduct energy evaluations, or committed on-site building energy managers to focus on energy investments. Creating building energy models can be financially prohibitive, require technical knowledge, and time commitments not suited to SCB stakeholders (Hong, Chou et al. 2000). Moreover, in many instances building energy models are beyond SCB stakeholders scope and do not meet fit-for-purpose (i.e. least level of complexity to meet a desired outcome) energy resource selection put forth by (Gaetani, Hoes et al. 2016). Therefore, measurement-based approaches may better suit small commercial stakeholders' requirements.

2.4.3 Measurement-based methods

Measurement-based approaches use empirical data to determine building energy profiles and include monitoring-based methods: sub-metering or outlet monitoring methods (Zhao, Lasternas et al. 2014, Ji and Xu 2015, Gandhi and Brager 2016) and non-intrusive load monitoring (NILM) (Norford and Leeb 1996, Farinaccio and Zmeureanu 1999, Berges, Goldman et al. 2010). Additionally, measurement-based methods include energy bill disaggregation, which uses energy bills to disaggregate using *top-down* or *bottom-up* methods (Wang, Yan et al. 2012). It is prudent to discuss smart meter and non-intrusive load monitoring methods to provide context for the use of energy bill disaggregation in this work.

2.4.3.1 Smart meters

A prominent technology warranting discussion in the context of this dissertation is the smart meter (U.S. DOE 2014). Supported by national grid modernization funding through *American Recovery and Reinvestment Act of 2009 Title IV: Energy and Water* (H.R.1 - 111th Congress 2009) and the *Energy Independence and Security Act of 2007, Title XIII: Smart Grid* (H.R.6 - 110th Congress 2007) smart grid investments have replaced an estimated one third of U.S. electricity customers' meters (U.S. DOE 2014). Smart grid technology has the potential to improve energy efficiency and increase customer engagement through customer-based systems (e.g. in-building displays or web portals) providing access to real-time energy usage (Schultz, Estrada et al. 2015).

However, smart meter energy disaggregation is currently incapable of providing end-use energy profiles without multiple points of reference, such as appliance level load signatures (Chahine, Drissi et al. 2011, Matsui, Yamagata et al. 2015), or when under imperfect scenarios, like supplemental electric space heating (Kipping and Trømborg 2016). Moreover, SCBs are highly heterogeneous in energy end-use profiles dependent on building use and occupant behaviors, further complicating smart meter benefits (Armel, Gupta et al. 2013). Until smart meter technology is fully developed and integrated into existing building stock SCB stakeholders will continue to rely on limited energy information.

2.4.3.2 Non-intrusive load monitoring

Non-intrusive load monitoring (NILM) technology is promising as a single point of measurement, non-invasive, and capable of disaggregate electricity load patterns over a circuit branch. NILM systems measure voltage and current, attempting to identify patterns, prior to disaggregating total energy consumption into the appliances or equipment drawing power

(Norford and Leeb 1996, Marceau and Zmeureanu 2000, Giri and Bergés 2015). Results have demonstrated that NILM software is capable of detecting equipment start-up and determining rates of deterioration for equipment power demand.

However, there are significant constraints, including time demands for system training, measurement discrepancy between commercially available devices, and data resolution versus software costs (Zoha, Gluhak et al. 2012). Ahmad, Mourshed et al. (2016) provide six considerations for selecting metering technology: (1) accuracy, (2) ease of deployment, (3) communication protocol, (4) granularity, (5) cost, and (6) availability. However, these considerations inherently assume that dedicated energy efficiency personnel are able to collect and are trained in analyzing the information that is output by monitoring equipment, which is less common a scenario in small commercial buildings (Trianni and Cagno 2012).

With technological advancements and increased market demand for energy efficiency, real-time energy monitoring methods will increasingly be adopted. However, current research trends have begun to shift from sub-metering data collection, citing high costs for implementation in buildings, to simplified disaggregation methods and algorithms as a bridge to when NILM and sub-metering technology become cost effective in small commercial buildings (Armel, Gupta et al. 2013, Iyer, Sankar et al. 2015, Ji, Xu et al. 2015).

2.4.3.3 Energy Bill Disaggregation

For the millions of small commercial building stakeholders, the primary point of contact with energy data is through monthly energy bills. Energy disaggregation provides a way to discern how energy is used in a building or space. Armel, Gupta et al. (2013) clarify the primary benefits to customers in obtaining this resolution of energy data, including realized energy reductions and savings, personalized energy improvement recommendations, and improved control of energy consumption. Two energy disaggregation methods are *top-down* and *bottom-up* (Wang, Yan et al. 2012).

The *top-down* method uses a utility bill and applies an end-use disaggregation algorithm to separate total energy consumption (electrical and heating fuel) into end-use categories. In residential, this is typically space heating and water heating for heating fuel, and cooling and base electrical load for electricity (Krigger and Dorsi 2009). One example of disaggregated commercial energy consumption developed by Akbari (1995) and Lawrence Berkley National Laboratory led to three end-use categories: HVAC, lighting, and miscellaneous loads. Results were comparable to DOE-2 energy simulation results, concluding that energy disaggregation could be done for commercial buildings, although algorithms become more complex as building intricacy increases, including use of elevators Akbari (1995). While top-down approach is the lesser time consuming approach of the two methods, top-down algorithms rely on generalized energy consumption not exhibited in the highly heterogeneous small commercial building sector with energy profiles varying across building activities, geographical regions, ages, and occupant behavior (Shapiro 2012, Barnes and Parrish 2015, Gandhi and Brager 2016).

A *bottom-up* energy disaggregation approach provides critical benefits to the small commercial audience, including: simplicity for a non-technical audience, transparency of calculations, trust in the information, and accessibility of required data (Iyer, Sankar et al. 2015). (W.L. Lee, F.W.H. Yik et al. 2003) presented a disaggregation algorithm for plug loads, lighting, and air conditioning, and applies the algorithm to large commercial buildings in Hong Kong. Findings suggested moderate accuracy of the developed disaggregation method; although, the study building contained residential units potentially skewing results. Menezes, Cripps et al. (2014) noted the bottom-up approach offers greater flexibility to estimate power demand and energy consumption, important traits when dealing with the small commercial audience who may lack well-established energy education.

A study by Robinson and Reichmuth (1992) combined energy audits with a disaggregation approach to quantifying end-use energy consumption. The authors separated seasonal (i.e. HVAC) and non-seasonal (i.e. lighting) energy systems to employ flat rate consumption to the non-seasonal end-uses, such that a weekly measurement of energy consumption for the non-seasonal systems could be extrapolated out to annual energy consumption. Iyer, Sankar et al. (2015) also separated weather-dependent and -independent loads in a case study, where a developed disaggregation algorithm was piloted across 94 stores of a single supermarket chain. Findings of the study demonstrated the power of disaggregated end-use data in identifying critical energy consuming parameters. In the case of the supermarket chain, Iyer, Sankar et al. (2015) note that occupancy was not a driver for energy consumption, counter to many commercial office buildings, and that refrigeration loads outweighed air conditioning loads.

In summary, NILM and sub-metering load disaggregation methods are counter to the tight profit margins and a lack of access to capital experienced by small commercial businesses (Farinaccio and Zmeureanu 1999, Birt, Newsham et al. 2012, Lanzisera, Dawson-Haggerty et al. 2013, Chrysopoulos, Diou et al. 2014, Shen and Wang 2014). Similarly, calculation-based energy quantification methods are too expensive and too reliant on a third party evaluator or dedicated energy manager. Use of bottom-up energy disaggregation in SCBs addresses the *barrier-motivator nexus*; where the financial cost of energy management services (barrier) prohibits the acquisition of information (barrier), further preventing the financial savings sought (motivator) (de Groot, Verhoef et al. 2001, Schleich 2004, Schleich and Gruber 2008, Gruber, Fleiter et al. 2011, Vassileva, Wallin et al. 2012, Cagno and Trianni 2013). Several whole building energy assessment tools providing disaggregated energy consumption information are freely available, or with limited access, to small commercial building stakeholders.

2.4.4 Available energy assessment tools

Prior to developing the building energy assessment resource, a search of publicly available energy analysis tools (i.e. tools that analyze whole building energy data and provide comparable results) was conducted. Three tools were discovered capable of whole-building energy disaggregation and applicable in small commercial buildings: Home Energy Saver, Commercial Building Energy Asset Scoring Tool, and the Small Commercial Toolkit (Regnier 2014, U.S. DOE 2015, U.S. DOE 2017).

Home Energy Saver (HES) program developed by Lawrence Berkley National Laboratory through the U.S. DOE (U.S. DOE 2015) is an example of a tool utilizing a bottom-up energy disaggregation. The tool provides energy information and recommended energy efficiency measures from user-input system data and building simulation. However, there are considerations for use in small commercial buildings. First, the tool is intended for use in residential buildings, but similarities may make it possible to adapt the tool to small commercial. Second, there are two versions of the tool, a simplified and professional. The simplified version may not be capable of distinguishing between a small commercial building and residence, while the professional version is too cumbersome for use by small commercial stakeholders. The other two tools are developed for use in small commercial buildings. These are discussed in detail in Chapter 6.0.

In conclusion, the three learning communities are capable of being educated on sustainable engineering and building sciences through educational mechanisms, including the classroom, service-based learning, energy audits and energy assessment resources. In the student community, consideration for the approaches to integrating sustainable engineering curricula is necessary to ensure students retain the knowledge taught. Moreover, the method for teaching sustainable engineering concepts should be engaging, which is available in service-based learning and flipped-classroom approaches. In homeowners, holistic energy audits better address homeowners’ complex barrier-motivator nexus by going beyond traditional motivators, primarily financial. In the small commercial community, financial and informational barriers, compounded by building heterogeneity, has left this group of buildings underserved. The culmination of this literature review is the research projects presented in the next five chapters.

3.0 UNDERSTANDING THE BENEFITS OF THE FLIPPED CLASSROOM IN THE CONTEXT OF SUSTAINABLE ENGINEERING

This chapter addresses research question 1, *can flipped-classroom pedagogies train and foster student learners and energy leaders, and does the collected data support the use of the flipped-classroom?* The research presented is a reproduction of an article in the *American Society for Engineering Education Annual Conference and Exposition conference proceedings*.

Marks, J., Ketchman, K. J., Riley, D. R., Brown, L. R., & Bilec, M. M. (2014). "Understanding the Benefits of the Flipped Classroom in the Context of Sustainable Engineering." Proceedings of the ASEE Annual Conference & Exposition, 1-13.

3.1 INTRODUCTION

Today, many engineering courses are taught using the traditional classroom lecture method. Students attend lecture, listen to their instructors deliver large amounts of information, and then attempt to apply this information outside of the class by doing homework. However, it has been noted that this form of teaching has shortcomings that could be impacting students' education and their ability to retain, analyze, and apply knowledge (Sams and Bergmann 2013). Some of the noted limitations include the small amount of teacher-student interaction, the rigid pace of the lecture, and that lectures only take advantage of one information delivery method (Toto and Nguyen 2009, Goodwin and Miller 2013). These disadvantages will not apply to every form of lecture, and some alternative interactive lecturing methods have been developed. In addition, the traditional lecture method can be useful for delivering large amounts of information in the small amount of class time provided. However, in some curriculum, specifically engineering, a strong emphasis on active learning can be beneficial to students.

To address this disconnect between delivery and student-learning, the flipped classroom teaching method has been gaining popularity. Additionally, reasonable technology is available to facilitate this delivery method. The flipped classroom often takes lectures normally given during class time and moves them outside of the classroom in the form of recorded videos or voice-over PowerPoint slides. The students watch the lecture on their own time and are able to pause, rewind, take notes, and re-watch the lectures as many times as is necessary to understand the material. These videos are usually accompanied by some kind of quiz to ensure students are watching the videos. During class, teachers take advantage of the time by employing active learning exercises that apply the knowledge learned from the lecture in a hopefully deeper way. This delivery method is intended to promote student-teacher interaction, problem solving and decision making skills, teamwork, leadership, and responsibility because the in-class activities tend to be teamwork based and critical thinking oriented (Zappe, Leicht et al. 2009). Flipping can allow students to take more responsibility for their education and the instructor to act as a guide, answering questions and helping students as questions arise. However, it has been noted that this method would not work well for larger class sizes, that there is a possibility of students not watching the videos, and that it is still not known if students can learn and connect with their instructor through video lectures in the same way as with traditional lectures (Lage, Platt et al. 2000, Brunsell and Horejsi 2013).

The problems associated with traditional teaching methods are especially important in the study of engineering. Engineering is a field that relies heavily on applying knowledge and using critical thinking to solve problems. While many undergraduate engineering courses are taught through lecture, applying the flipped classroom teaching method can give students an opportunity to improve application and critical thinking skills through in-class discussions and activities. The University of Pittsburgh (UPitt) and the Pennsylvania State University (PSU) flipped two undergraduate engineering courses and studied the effects on student learning as well as student perception of classroom environment in the seven psychosocial dimensions: personalization, involvement, student cohesiveness, satisfaction, task orientation, innovation, and individualization.

3.2 CLASS INFORMATION

The Pennsylvania State University is a public university with 16,719 full time undergraduates and 10,297 graduate students. The flipped class contained 33 students of mixed majors and years in school, but was predominately civil and environmental students. The class was CEE 1218/2218-Design for the Environment, an experiential learning course in which students are challenged to apply concepts of sustainability through tangible and appropriate projects carried out with a partnering community/project. The University of Pittsburgh is a public university with 36,749 full time undergraduates and 6,418 graduate students. The flipped class was of similar design and make-up, containing 12 students of mixed majors and years in school.

Both classes were pilot programs for a National Program. This National Program is a joint program under development at the University of Pittsburgh and Pennsylvania State University and is designed to teach students about home energy efficiency and sustainability and empower them to conduct home energy assessments in their community. The design of the program reflects the need for alternative models to personally engage homeowners in a holistic approach to home energy and sustainability concepts and also respond to the limitations of traditional professional home energy audit processes that are focused on motivating homeowners to invest in home energy improvements (D. Riley, M. Whelton et al. 2012) The multifaceted program begins in the classroom where students are first taught about energy assessments and the home as a system in a flipped-classroom education model, and then provided hands-on training in the performance of in-home energy assessments and culminates with a student-authored personalized educational report to homeowners on their home's energy profile and ways to improve efficiency, safety, and health.

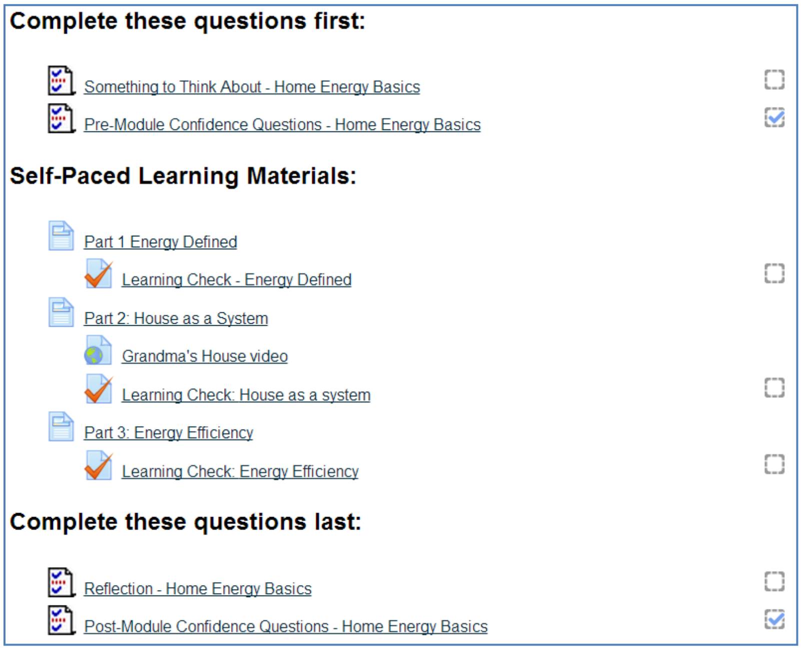
The semester-long course is designed to teach students technical information in the major concentrations of home energy assessments, health and safety, building materials, air infiltration, heating and cooling, and energy management and security. Unique to the course are modules dedicated to developing trust and being respectful of the variable world views they may encounter during home energy assessments. Near the end of the course, students complete two home energy assessments. In teams of three or four, students ideally perform their first "practice" assessment in the friendly environment of a faculty member or another accessible location with support from a teaching assistant. The second assessment, also the student's final project, takes place in a home outside of the university community identified through collaboration with neighborhood organizations or other trusted community-based networks. Each team was assigned a home in their respective city and performed the assessment with minimal support by the teaching assistant. Students delivered an energy assessment report to the homeowners, providing the homeowner with a general overview of their current energy profile, health and safety topics, and energy improvement recommendations.

The report delivered to the homeowner is personalized to their worldview and cognitive style, determined through a survey performed at the time of the assessment, and the home's current energy profile, obtained through the assessment and utility bills collected. The report is meant to inform the homeowner of ways to improve their energy use through retrofits or upgrades and educate them on how these energy efficiency measures (EEM) will improve their energy use as well as the comfort and safety of the home.

3.3 METHODS

3.3.1 Module Tests

Throughout both courses, lectures were moved out of the classroom in the form of video presentations. Each of the ten modules consisted of anticipatory questions, a pre- and post-module confidence test, videos and learning check quizzes. Videos were limited to three to eight minutes. The results of the pre-and post-confidence questions are intended to be used as key indicators of student gains. These questions are presented prior to the first video in a module and also at the end of the module as follows: “How confident are you in your: *Ability to (insert relevant content here for example describe how we use energy in our homes?)* 1: Not a Clue; 2: Not Confident; 3: Somewhat Confident; 4: Confident; 5: Very Confident.” A screenshot of a module can be seen below in Figure 7.



Complete these questions first:

- Something to Think About - Home Energy Basics ☐
- Pre-Module Confidence Questions - Home Energy Basics ☑

Self-Paced Learning Materials:

- Part 1 Energy Defined
  - Learning Check - Energy Defined ☐
- Part 2: House as a System
  - Grandma's House video
  - Learning Check: House as a system ☐
- Part 3: Energy Efficiency
  - Learning Check: Energy Efficiency ☐

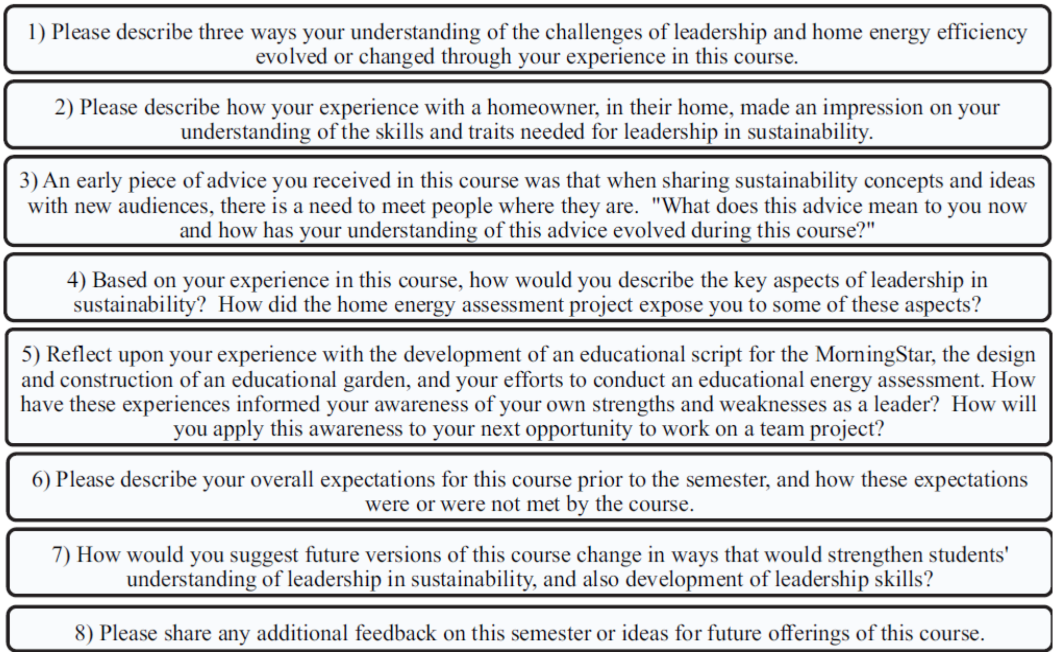
Complete these questions last:

- Reflection - Home Energy Basics ☐
- Post-Module Confidence Questions - Home Energy Basics ☑

Figure 7. A screenshot of module 3 serves as an example of the typical module set-up

3.3.2 Course Reflection

In addition to the module pre- and post- tests, a survey was given to students at the end of the class. The survey consisted of eight questions relating to the experiences the student had in the class and what their opinion on these issues was. Questions used in the survey can be seen in Figure 8.



1) Please describe three ways your understanding of the challenges of leadership and home energy efficiency evolved or changed through your experience in this course.

2) Please describe how your experience with a homeowner, in their home, made an impression on your understanding of the skills and traits needed for leadership in sustainability.

3) An early piece of advice you received in this course was that when sharing sustainability concepts and ideas with new audiences, there is a need to meet people where they are. "What does this advice mean to you now and how has your understanding of this advice evolved during this course?"

4) Based on your experience in this course, how would you describe the key aspects of leadership in sustainability? How did the home energy assessment project expose you to some of these aspects?

5) Reflect upon your experience with the development of an educational script for the MorningStar, the design and construction of an educational garden, and your efforts to conduct an educational energy assessment. How have these experiences informed your awareness of your own strengths and weaknesses as a leader? How will you apply this awareness to your next opportunity to work on a team project?

6) Please describe your overall expectations for this course prior to the semester, and how these expectations were or were not met by the course.

7) How would you suggest future versions of this course change in ways that would strengthen students' understanding of leadership in sustainability, and also development of leadership skills?

8) Please share any additional feedback on this semester or ideas for future offerings of this course.

Figure 8. Questions of the final course reflection given to students at the end of the semester.

Thirty students (100% response rate) completed the survey in the class; twelve (100% response rate) completed the survey in the UPitt class. All students were assigned a number from one to 30 or a letter from A to L in order to preserve anonymity. The answers from students in each section were then codified in order to find trends in student opinions and ideas about the class. Codes in qualitative data analysis are tags, names, or labels and coding is the process of putting tags, names, or labels against pieces of data. In Miles and Huberman (1984) there are two main types of codes: descriptive codes and inferential (or pattern) codes. Descriptive codes are early labels, requiring little or no inference beyond the piece of data itself, while pattern codes require some degree of inference beyond the data and pull the material into smaller, less abstract, meaningful units. This method of first descriptively codifying followed by creating pattern codes was used to identify themes in student responses which could then be recorded into a numerical representation of the frequency of the codes.

3.3.3 College and University Classroom Environment Inventory

Along with the above two methods, a third was used only in the UPitt class. The College and University Classroom Environment Inventory (CUCEI) survey was given to 22 students at the end of the semester, and is used to assess students' perceptions of the following seven psychosocial dimensions of classroom environment; student cohesiveness, individualization, innovation, involvement, personalization, satisfaction, and task orientation. This test has been used to assess classroom environment as opposed to the direct observation approach due to the benefits that come from a student’s perspective and the possibility that an observer could miss or consider data unimportant. It was developed specifically to assess the class environment in smaller, university level classes and therefore has been used previously in higher education as a valuable tool (Pulvers and Diekhoff 1999, Coll, Taylor et al. 2002). The test was administered and scored by the Engineering Education Research Center at PSU.

Table 5. Explanations for the seven psychosocial dimensions of classroom environment.

Student Cohesiveness:	Students know, help, and are friendly to one another
Individualization:	Students can make decisions; students treated differentially/individually
Innovation:	Instructor plans new/unusual class activities, assignments & teaching techniques
Involvement:	Students participate actively/attentively in class discussions & activities
Personalization:	Opportunities for students to interact with instructor; concern for students' welfare
Satisfaction:	Enjoyment of classes
Task Orientation:	Class activities are clear & well organized

This survey is done by giving students a list of 49 statements and asking them to rate Strongly Agree (1), Agree (2), Neutral (3), Disagree (4), or Strongly Disagree (5). This scale is reversed for half of the questions to ensure full participation in the reflection survey and that students are not brushing aside reading the question before answering. There are seven statements for each of the seven above psychosocial dimensions, and statements include those such as “The instructor considers students’ feelings,” and “Each student knows the other members of the class by their first names.” The score for the class is then calculated and given as a number out of five with five being the best (Fraser and Treagust 1986). Additional explanations of the seven psychosocial dimensions of classroom environment are illustrated in Table 5.

3.4 RESULTS

The results of the module tests, final course reflection, and the CUCEI are summarized. After analyzing the results from PSU’s pre- and post-confidence tests, there was an increase in confidence. The questions were answered on a scale from 1 to 5, 5 being ‘Very Confident.’ The mean answer for all of the pre-module tests was 2.75/5 with the post-module tests’ mean of 4.27/5: an increase of +1.53. The frequency of the responses ‘No Clue’, ‘Not Confident’, ‘Somewhat Confident’, ‘Confident’, and ‘Very Confident’ also changed. There was an increase in ‘Confident’ and ‘Very Confident’ answer frequency accompanied by an overall decrease in ‘No Clue’ ‘Not Confident’ and ‘Somewhat Confident’ answer frequency from the initial test before using the learning module to the post-test afterwards, see Figure 9A..

Similar results were seen with the UPitt class. The mean answer for all of the pre-module tests was 2.66/5 with the post-module tests’ mean of 3.98/5: an increase of +1.32. Additionally, there was an increase in ‘Confident’ and ‘Very Confident’ answer frequency accompanied by an overall decrease in ‘No Clue’ ‘Not Confident’ and ‘Somewhat Confident’ answer frequency, see Figure 9B.

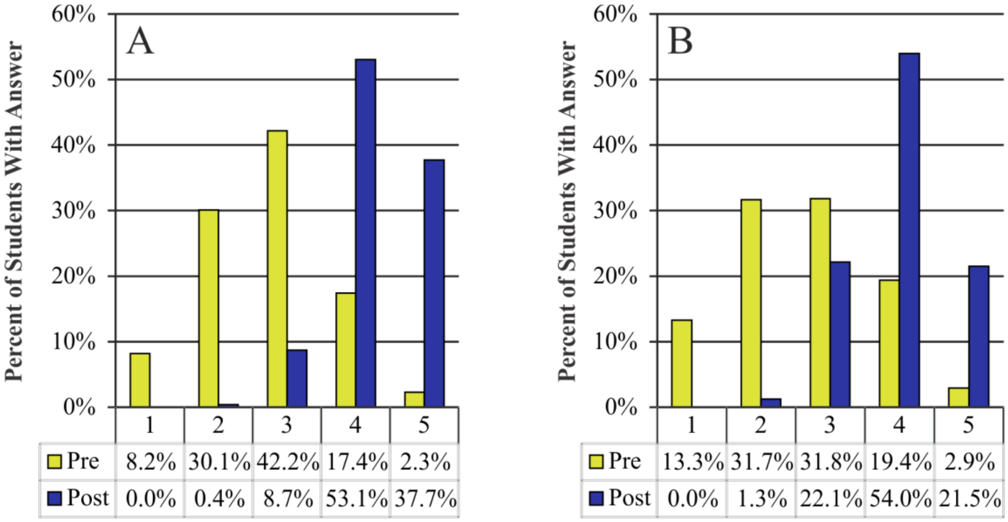


Figure 9. Responses to pre- and post-module confidence questionnaire. A) average frequency of answer for the pre-tests and post-tests for PSU; class size: 30; B) average frequency of answer for the pre-tests and post-tests for UPitt; class size: 12; 1 = No Clue, 2 = Not Confident, 3 = Somewhat Confident, 4 = Confident, 5 = Very Confident.

After analyzing the answers to the final course reflection survey, some trends were identified. Although the questions did not directly ask about the flipped classroom teaching method, advantages associated with it were frequently mentioned in the student responses. More than half of the PSU students (16/30) stated that they frequently were able to put their class knowledge to use during activities of the class and that they learned skills that are useful for their future or their future careers. Some of the skills mentioned include adaptability (15/30), leadership (18/30), and communication (18/30). Five students made a point to say they liked the flipped classroom structure; although, the questions made no mention of it, and more than half of the students had something positive to say about the class. For example, Student 8 said, "*I really enjoyed the flipped classroom style of learning and benefited from it. I thought it created a more comfortable learning environment in class and allowed students to learn in their own way at home*." Similarly, Student 2 wrote "*…during this semester I found team work is really more interesting than working individually*."

The UPitt course had similar outcomes. More than half of the students had extremely positive view of the class such as this opinion shared by Student C: "*This unconventional way of teaching with time spent at the morning star [sic] classroom discussions and hands on work proved to make the class great!*" A majority of students shared that they learned communication skills (9/12) and leadership skills (11/12), and many students wrote that they learned to customize their arguments to their audience (10/12), learned to understand different points of view (10/12), and learned something new about themselves (9/12). Like the UPitt class, students here stated that they used knowledge from class during their active learning activities and that they gained skills and knowledge that will be useful in the future. Along with learning from the active learning activities, over half wrote that they enjoyed doing the hands on activities and specifically the Home Energy Assessment project done with the National

Program, which allowed them to interact with homeowners and apply their knowledge of energy use in homes. This can be seen in these quotes by Student F and Student J:

"The modules really helped me to increase my knowledge about systems and general topics of sustainability….I like that we had the possibility to do things in reality such as the Home Energy Assessment."

"… [We] apply this knowledge in the field so that the knowledge is not lost and becomes a skill."

Six students in the UPitt class and five in the PSU class mentioned how the video modules helped their learning. One student stated "*I enjoyed the online lectures not only because they were short but also I remembered the material easier than if someone were to lecture all of the material straight through (the short videos and questions in between stimulated my thoughts easily).*" Another wrote, "*I think the content of the class was made very easy to understand through the modules*."

Table 6. Results of PSU course's CUCEI. Sample size = 22.

Dimension	Average Score
Student Cohesiveness	3.20
Individualization	3.01
Innovation	3.22
Involvement	3.94
Personalization	3.99
Satisfaction	3.79
Task Orientation	3.85

Very few students in either class had anything negative to say about the course. A few suggestions were: using more physical papers, having a place online to discuss the lecture with classmates, better utilizing class time, having a more structured schedule, teaching to a smaller class size, and wanting to cover details that are more technical. These challenges were brought up by no more than four students and are all common challenges associated with the flipped classroom teaching method.

The final method of data collection was only performed at PSU. The College and University Classroom Environment Inventory (CUCEI) survey was given to students at the end of class. The results of this test are shown below in Table 6, with a score of three or above in each of the seven categories.

3.5 DISCUSSION

Students in both courses frequently expressed that they learned various personal skills such as leadership, listening, and communication, which were consistent with the class objectives and advantages noted in the literature. The tones of the student responses were generally positive, and on the CUCEI, the students scored the class environment above average. This suggests that students were open to classes being taught in this way, and that there are benefits associated with the flipped classroom that are not available through traditional lecturing methods.

From the above data, it can be seen that the class was successful in teaching the students the material. This is evident from the large increase in confidence from the pre-module tests to the post- module tests. It can be concluded that the modules are a feasible way to present the information and that students are able to learn from them. However, a control group would be needed to see if the students' confidence increased on a scale that is comparable to traditional teaching methods.

Along with the affirmation of learning found by the pre- and post- tests, the themes found in the final course reflection answers show an overall positive view of the class, with little to no complaints related to the flipped structure. It can be seen that many personal and professional skills such as leadership, communication, adaptability, understanding of differing views, and personal strengths and weaknesses were emphasized. Within the final course reflection survey, many students noted learning the importance of these skills. This accomplishes the three course objectives seen below:

1. Formulate and design solutions that take into account the effects of worldview on the motivation and behavior of individuals.
2. Communicate project results and solutions to community-based audiences in both written and oral form.
3. Articulate personal awareness and participate in self-assessment and reflective activities that are focused upon the awareness and cultivation of leadership skills.

Gaining these professional skills is also an outcome that is consistent with advantages found in the literature on flipped classrooms. Researchers Lage, Platt, and Treglia noted that students taught using the flipped classroom method developed communication skills and improved their potential job skills (2000). They also noted an increase in student responsibility and increased opportunities for critical analysis. This can be seen in the classroom of the UPitt course through this quote by one student: "*I like the form of this kind of class [sic] we learn by ourselves at home and discuss what we learned in class*." Similarly, a paper by He, Swenson & Lents noted that using videos as opposed to lectures allowed students to pause, take notes, look at the textbook, and rewind to better understand the material and move at a personal pace (2012).

A student in the host course conveyed approval of the video lectures in a quote taken from the CUCEI survey:

> *"The modules in general were great. During the videos, I continuously stopped and wrote down all additional information and when I couldn't remember something I just looked up in my notes. I also liked to [sic] online tests after to check the knowledge to make sure I understood. It was great that there was always enough time in class to ask about the modules and topics I didn't understand."*

Similar quotes can be seen throughout the surveys pointing to a positive student perception of the course. This was confirmed with the results of the CUCEI. In all seven categories, the students scored the course higher than average (2.5/5) with the highest score being 3.99/5 in the category of 'Personalization'. Personalization is defined as the availability of opportunities for students to interact with the instructor and whether or not the instructor appeared concerned with the success of the students. This result is consistent with the literature review advantage that flipping the classroom will provide students with more teacher interaction and allow teachers to connect personally with their students. The second highest scored category on the CUCEI was 'Involvement' with a 3.94/5. The involvement category is meant to measure student's participation in in-class activities and class discussions. By moving the lectures out of the classroom, not only does it take a passive student centered class and turn it into an active learning environment, it also frees up time for more activities and discussions (Toto and Nguyen 2009). The results of the CUCEI agree with this.

In addition, because the students scored the CUCEI higher than average, it can be inferred that this above average class environment would have a positive effect on the student's learning. Research has shown strong correlations between classroom environment and student outcomes, such as the 1972 study by Walberg, which reinforced Bloom's theory that measurements on the same characteristics can be predicted when considerations of environment are included (Bloom 1964, Walberg 1972). Fraser and Treagust (1986) found that classes with better environments, those containing cohesiveness, organization, goal direction and satisfaction, also saw greater outcomes on a variety of measures. Because of the high scores given by the students of the UPitt class, it is evident that the flipped classroom environment is one that promotes learning and achievement.

3.6 CONCLUSION

Through this research, it has been found that the students of the two flipped engineering courses felt they learned valuable skills for the future such as communication, leadership, and teamwork. They also noted that the time used in class for group discussion was helpful to them, and that through active learning activities, they were able to put the knowledge they learned in class to use as a skill. There was a general increase in confidence across both classes after completing the learning modules, which many stated were helpful. There was also evidence of a greater connection between the teacher and the students through the high scores in the 'Personalization' and 'Involvement' categories of the CUCEI. These results point to a successful course and a positive perception of the flipped classroom by students suggesting this method could be used in engineering classrooms in the future.

As discussed in this chapter, flipped-class design fosters problem solving and decision making skills, in addition to a sense of teamwork, leadership, and responsibility, which are elements necessary when working in larger communities. The findings of this research support the concept of community interconnectedness at the student learning community. When considering the three levels of sustainable engineering education, previously discussed in Chapter 2.0 section 2.1, the flipped-class energy assessment course examined is a first step, from the bottom-up, to educating students in building energy science.

4.0 SUSTAINABLE ENGINEERING COGNITIVE OUTCOMES: EXAMINING DIFFERENT APPROACHES FOR CURRICULUM INTEGRATION

This chapter addresses the second part of research question 1, *how do student outcomes, in the context of sustainability, differ between these approaches, and what do these outcomes suggest for the continued integration of sustainable engineering to curricula?* The research presented is a reproduction of an article in the ASCE *Journal of Professional Issues in Engineering Education and Practice*.

Ketchman, K. J., Dancz, C. L. A., Burke, R. D., Parrish, K., Landis, A. E., & Bilec, M. M. (2017). “Sustainable Engineering Cognitive Outcomes: Examining Different Approaches for Curriculum Integration.” Journal of Professional Issues in Engineering Education and Practice, 143(3). doi:10.1061/(ASCE)EI.1943-5541.0000324

4.1 INTRODUCTION

Challenges facing engineers demand complex sustainable engineering solutions. Pressing environmental issues such as climate change, resource depletion, and water scarcity are indiscriminate, crossing national borders and affecting global populations. Sustainable engineering balances technological advancements and anthropogenic repercussions to meet the needs of today without compromising future generations’ ability to meet theirs. These challenges are recognized by educators, professional engineering societies, and accreditation organizations, including Brundiers and Wiek’s work on sustainability research education, the American Society of Civil Engineers (ASCE), the Accreditation Board for Engineering and Technology (ABET), and the National Academy of Engineering (ASCE 2008, Brundiers and Wiek 2011, ABET 2015, NAE 2015). The National Academy of Engineering outlines fourteen Grand Challenges for Engineering, intended to engineer a more sustainable future. In the 21st century these institutions have ingrained sustainability into their core criteria, solidifying sustainability as a primary outcome of students’ education.

The ASCE Body of Knowledge Second Edition (BOK2) embedded sustainability into their student outcomes, establishing prerequisite educational attainment of a body of knowledge prior to licensure and professional practice (ASCE 2008). The BOK2 defines student achievement in sustainability outcomes as the application of sustainability principles to engineered systems, defining measurable levels of student cognition (i.e., Bloom’s taxonomy) specific to sustainability (Bloom, Engelhart et al. 1956).

As previously noted, proposed changes by ABET to Engineering Accreditation Commission (EAC) criteria would remove the term *sustainability* from Criterion 3 Student Outcomes, item (c), and Criterion 5 item (b) (ABET 2015). Whether the proposed approach by

ABET to restructure the inclusion of sustainability to accreditation metrics is successful will be a point of consequence, necessitating monitoring.

Further, these changes could potentially impact international accreditation through the *Washington Accord*. The International Engineering Alliance is a consortium of accrediting institutions, which signed the *Washington Accord* in 1989 recognizing equivalency in member accreditation qualifications. This agreement affords reciprocity between its seventeen international members, stating decisions made by one member are acceptable by all others, including ABET.

As part of the current ABET criteria, prior to entry to professional practice of engineering, students complete a “major design experience” incorporating the knowledge gained through their academic career, similar to BOK2 requirements, Criterion 5. Senior design is the culmination of a student’s collegiate career where they apply their learning in development, design, and application of a rigorous multi-faceted project. In Civil and Environmental Engineering (CEE) programs, these projects typically include team projects integrating sustainable engineering, construction management, structural design, geotechnical analysis, water management and infrastructure.

Senior design courses are structured around amassing the civil engineering body of knowledge into a semester-long design project. Over time, the senior design courses have the potential to essentially ‘stockpile’ many ABET outcomes, potentially leading to dilution of the outcomes and the true intention of senior design and other outcomes such as sustainability. What I argue in this research is that while senior design needs to be multi-faceted to produce well-rounded engineers, *the assessment* of ABET outcomes, especially sustainable engineering, should be done in other courses. However, best practices for the incorporation of sustainability into curriculum are debated, with three approaches emerging: module-based, stand-alone and senior design, further described in subsequent sections (Fogarty 1991, Zhang, Vanasupa et al. 2012).

In this research, I examine the stand-alone approach implemented at two universities, evaluating student outcomes in comparison to the senior design approach (Dancz, Ketchman et al. 2017 accepted), in the context of sustainable engineering. First, a review of literature surrounding the three approaches to sustainability curriculum integration: stand-alone, module-based and senior design, and existing sustainability rubrics is presented. Next, a detailed description of the participating courses is conferred, followed by the evaluative methods including outlining the holistic sustainability assessment tool. Results are presented and organized by the assessment tool's evaluative components, culminating in recommendations.

4.2 APPROACHES TO INTEGRATING SUSTAINABILITY IN ENGINEERING

Sustainable engineering introduces a holistic philosophy to Civil and Environmental Engineering (CEE) engineering curricula (i.e., the three pillars of sustainability and their interconnectivity), reinforcing systems-level thinking existing in engineering education (Cattano, Nikou et al. 2011). A review of three approaches to sustainable engineering integration focuses on module-based and stand-alone pedagogies, offering perspective on the debate over best methods to integration of sustainability in engineering (Fogarty 1991, Boyle 2004, Boks and Diehl 2006, Zhang, Vanasupa et al. 2012, Antaya, Bilec et al. 2013, Shields, Verga et al. 2014), in addition to senior design, which is driven by accreditation and a culminating experience (ASCE 2008, ABET 2015).

4.2.1 Module-based approach

In the module method, engineering programs integrate sustainability throughout a host of existing courses by threading individual sets of course skills together in an effort to reach higher levels of intellectual behavior via interdisciplinary concept connection (Fogarty 1991). The Center for Sustainable Engineering, a partnership between Syracuse University, Arizona State University, Carnegie Mellon University, Georgia Institute of Technology, and University of Texas-Austin, developed sustainable engineering modules designed for easy incorporation to existing courses; other entities can and have provided modules to the CSE website as well (Allenby, Murphy et al. 2009, Davidson, Hendrickson et al. 2010). Another notable example of the module method is the Engineering Sustainable Engineers program at the University of Texas-Arlington, where Civil Engineering, Mechanical Engineering, and Industrial Engineering departments implement sustainability modules to infuse sustainability into engineering curricula (Weatherton, Sattler et al. 2012). Additional examples of module-based approaches with varying degrees of sustainability, include, but are not limited to: (1) University of Colorado inclusion of topics in sustainability to first-year civil and environmental engineering students required 1-credit courses, (2) Colorado State University building information modeling course teaching building energy efficiency (Lewis, Valdes-Vasquez et al. 2015), and (3) the US Air Force Academy incorporation of sustainable engineering modules into freshman introductory courses (Christ, Heiderscheidt et al. 2015). In summary, many of the module-based approaches are used to incorporate sustainability into existing courses, and in some instances acting as an introduction to sustainability early in students' academic careers (e.g., freshman or sophomore), promoting further incorporation of sustainability in their junior and senior level courses (Bielefeldt 2011).

4.2.2 Stand-alone approach

In the stand-alone approach, a program establishes distinct, stand-alone courses focused on topics in sustainability and incorporating these courses into the students' curriculum. A 2005 benchmark study performed by Center for Sustainable Engineering (CSE) identified and surveyed 137 sustainable engineering champions (155 courses), representing 97 of 365 U.S. institutions containing an ABET accredited engineering program. Responses indicated nearly half of reported courses contained sustainable engineering as a dominant theme (i.e., greater than 50% of content on sustainable engineering). Further, the stand-alone course appeared to be the most common approach used in the 155 courses, while the authors recognized the other approaches examined as being widely used, including the module-based method (Allen, Allenby et al. 2008). The report does not suggest that either approach offered in the report is preferred, stating that each approach has its positives and negatives. Additionally, the CSE benchmark study asked about class size and make-up, gleaning from the sample of courses that the sustainable engineering courses were directed towards upper division (junior and senior undergraduates) and graduate students, accounting for 90% of students taking sustainable engineering courses.

A follow up survey distributed at the 2010 national meeting of Civil and Environmental Engineering (CEE) department heads, intended as an update to the CSE report (Bilec, Hendrickson et al. 2011). The 2010 survey focused on CEE programs only, collecting 64 surveys representing 25% of ABET accredited CEE programs. A comparison of the 2005 benchmark and 2010 survey results, although different population samples, indicated minimal change over the period, such as a continued interest in sustainable engineering with 89% of participating universities offering sustainable engineering courses; 88% of civil, architectural, and environmental disciplines in 2005. Further, 19% of participating departments in the 2010 study reported offering three or more course containing sustainable engineering in the title, up slightly from 16% in the 2005 benchmark (Bilec, Hendrickson et al. 2011).

4.2.3 Senior design approach

The senior design approach can be viewed as partially a result of accreditation and professional societies' inclusion of sustainability to requisite outcomes. Specifically, ABET and the ASCE BOK2 have incorporated sustainability requirements (ASCE 2008, ABET 2015). As the leading accreditor in the U.S. of engineering programs, meeting ABET requirements is one manner in which universities offering degrees in engineering have incorporated sustainability into the senior design course. Moreover, BOK2, developed by ASCE, outlines a list of 24 educational outcomes, including sustainability, to be attained by students prior to professional practice.

Stand-alone courses can provide sustainability-centered specialization from instructors and rubrics, designed to engage students in higher levels of cognition; contrary to senior design projects, which are devised around students' application of cumulative engineering disciplines learned through prior courses, and demonstrating competence through multi-faceted design projects. These projects act as an end-point cognitive evaluation of a student's knowledge in his or her respective focus area within the CEE field (e.g., transportation, water management, or structures). However, a review of literature shows a lack of quantitative research on the senior design approach to incorporating sustainable engineering principles.

4.2.4 Sustainability rubrics

Prior to evaluation of sustainability, it was necessary to first examine different approaches to assess sustainability, a necessary and complex endeavor and further explored in (Dancz, Ketchman et al. 2017 accepted). Approaches to evaluating student outcomes from engineering courses explicitly in the context of sustainability include, but are not limited to: assessment of students' projects for holistic understanding of the three pillars of sustainability (McCormick, Lawyer et al. 2015), volume of incorporation of sustainability topics in discussion (Bielefeldt 2013), and instructor-created or pre-established rubrics, such as the Sustainability in Higher Education Assessment Rubric (SHEAR) (Riley, Grommes et al. 2007, Mckeown 2011). SHEAR rates a course's performance in eight categories: awareness and knowledge, skill development, application in diverse settings, reflection, responsibility, diverse interactions, partnerships, and life-long learning. Additionally, Bloom's Taxonomy (Bloom, Engelhart et al. 1956) is a widely accepted and implemented method for measuring students' cognitive levels, including in the context of sustainability (Anderson, Krathwohl et al. 2001, Näsström 2009, Krathwohl 2010, Pappas, Pierrakos et al. 2013), and has been incorporated to ASCE BOK2 (ASCE 2008). However, often used independently, these evaluative methods provide evaluators with isolated understanding of students' sustainability knowledge.

Harmonization of three evaluative methods (Bloom, Engelhart et al. 1956, Bielefeldt 2013, McCormick, Lawyer et al. 2015), with the addition of two metrics measuring quantitative incorporation and identification of specific sustainability topics incorporated, offers greater clarity of student learning at the cognitive and application level (Dancz, Ketchman et al. 2017 accepted). This research focuses on stand-alone and senior design approaches to integrating sustainability into engineering and examines potential variation in student outcomes using a holistic assessment rubric derived from existing evaluative methods.

4.3 METHODS

This project intends to evaluate student outcomes, in the context of sustainability, by comparing students' projects collected from stand-alone sustainable engineering and senior design courses. In this section, I present course descriptions, project expectations and data collection processes for the stand-alone and senior design course projects, followed by identification and explanations of the evaluative metrics integrated into the holistic assessment rubric, including coding schemes. Lastly, the applied inter-relater reliability approach is discussed to eliminate bias in evaluation of projects.

4.3.1 Stand-alone course project descriptions

A stand-alone sustainable engineering course was selected from each university's department of civil and environmental engineering for participation in this research; see Table 7 for a summary of project distributions. The Arizona State University (ASU) course, Earth Systems Engineering and Management (ESEM), is a multi-disciplinary engineering course that focuses on design and management in the context of human activities and the three pillars of sustainability. ESEM is a junior- and senior-level course, not containing graduate-level students. The University of Pittsburgh (UPitt) course, Engineering and Sustainable Design (ESD), is a course dealing with sustainable design in engineering, infrastructure, communication, manufacturing and community.

ESD contains students from junior-, senior-, and graduate-levels; all graduate student projects were removed from ESD projects analyzed for this research.

Table 7. Distribution of projects by semester and year for the examined courses

			Count of Projects			
Course	Semester	Year	Individual	Groups	(students)	Total Students
ASU						
ESEM	Fall	2014	21	24	(66)	87
ESEM	Spring	2015	6	21	(85)	91
UPitt						
ESD	Fall	2013	-	6	(30)	30
ESD	Fall	2014	-	7	(30)	30
Senior Design						
University A	Spring	2014	-	12	(73)	73
University A	Fall	2014	-	6	(41)	41
University A	Spring	2015	-	10	(67)	67
University B	Spring	2014	-	5	(43)	43
University B	Fall	2014	-	4	(27)	27
University B	Spring	2015	-	6	(36)	36

Note: ASU = Arizona State University; UPitt = University of Pittsburgh; ESEM = Earth Systems Engineering and Management; ESD = Engineering and Sustainable Design

Projects were collected from ESEM for the fall 2014 (45 projects) and spring 2015 (27) semesters, totaling 72 projects. In 2014, the project theme was “myth-busting” where students analyzed sustainability claims for validity. Projects included comparison of electric versus traditional vehicles, i.e., using modeling software to quantify greenhouse gas emissions from vehicle operation and electric grid supply. Other topics covered by students included food deserts, waste recycling, building lighting, and renewable energy resources. The project theme for 2015 was “global sustainability challenges,” and students defined problems that had global implications. Projects included assessing impacts of population growth on the Florida

Everglades, by identifying cultural, environmental and economic impacts of rising oceans, in addition to topics in sustainability ethics, carbon sequestration, and resource depletion. It should be noted that in 2014, students were given the opportunity to select research topics from a list, and the overwhelming majority of students opted to do so, while the 2015 class determined their own research topics. However, research topics from both years were well-distributed throughout a broad range.

As part of the project expectations, students were responsible for several deliverables and milestones throughout the semester. These include submission of a proposal of research and progress reports, prior to the final report. In their proposal of research, students outline initial project design (i.e., scope, methods, and timeframe) to be reviewed and approved by the instructor. Progress reports presented the developmental steps of students' projects from research through analysis, intended to identify issues and direct students towards corrective actions. Students' final reports were required to include design of experiments and analysis of results, in which students were to derive their recommendations (i.e., should someone adopt a new strategy based on the findings). Final reports were evaluated and graded, independent of this research, according to their qualitative (i.e., general writing rubric, problem statement) and quantitative contributions, including design of experiment.

ESD projects were collected from years 2013 (6 projects) and 2014 (7), totaling 13 projects. Projects from 2015 were submitted in-person and returned to students for their keeping and were not available for incorporation to this research. Students in 2013 participated in developing solutions to First Lady Michelle Obama's *Let's Move!* Campaign, which aims to curb childhood obesity through increased activity, decreased screen time, and increased awareness about the benefits of healthy foods (First Lady Michelle Obama 2010). Working with local communities, students connected human health with urban infrastructure improvements (e.g., bike lanes, greenways, or food deserts) before evaluating proposed solutions for environmental, economic, and societal effects. Fall 2014 projects focused on living laboratories (Voytenko, McCormick et al. 2016) and campus-level sustainability improvements as part of a university-wide initiative calling for greater investment in sustainability from all colleges and departments. Course projects included evaluation of renewable energy installations, estimations on the benefits from green roofs, assessment of societal impacts from community gardens and design of net-zero water dormitories.

Similar to ESEM, students were responsible for several deliverables, including proposal of research and progress reports prior to the final report. In both semesters, students were tasked with deriving their own schedule for meeting the following deliverables: submission of an outline, drafts at 50% and 90% completion, and the final report. Students were expected to apply quantitative methods taught during the course to their final report, including life cycle assessment, decision matrix, and energy modeling. This was reflected in grading rubrics which incorporated qualitative (i.e., general writing rubric, problem statement) and quantitative metrics.

ESEM and ESD were taught by Amy Landis and Melissa Bilec, respectively. However, these instructors were not involved in the evaluation of course or senior design projects for this research. Evaluation of student projects related to the research (not grading) was performed by Kevin Ketchman, Claire L. A. Dancz, Rebekah Burke, and a graduate student researcher. No evaluators had investment in the performance of course or senior design projects, and no evaluators acted as co-instructor or teaching assistant in these courses. Projects were dispersed between evaluators, evenly distributing projects according to university, class, and semester, allaying bias.

4.3.2 Senior design project descriptions

Senior design projects were collected from two universities for Spring 2014, Fall 2014 and Spring 2015 semesters, summarized in Table 7. To protect the confidentiality of instructors, the senior design courses and affiliated university are withheld and are referred to as University A and University B. University A senior design projects are identified by the instructor through partnerships with industry, typically focusing on large-scale land development, and are assigned to teams of five to seven students. Students submit plans for a comprehensive land development project, including traffic circulation, water, wastewater, structural, surveying, and geotechnical analysis; thus, they require a comprehensive set of civil engineering skills. Students author a formal submittal package including report, technical drawings, and calculations supporting their recommendations, which is presented to the client and instructor at the end of the course. Similarly, University B identifies projects through industry collaboration, encompassing engineering design simulated from real-world engineering projects. Long-standing relationships with the department of transportation and city partners has made available heavy highway and bridge projects, while continued collaboration with Engineers Without Borders has made one to two international water infrastructure projects possible each semester.

At both universities, a senior design *project rubric* evaluates sustainability in the final report (i.e., points are given for including sustainability); University A rubric contains an explicit sustainability metric, while University B includes sustainability as part of a larger category of constraint considerations, including economic, environmental/sustainability, manufacturability/constructability, ethical/health and safety, and social/political.

4.3.3 Evaluative method

Previous research indicated limited focus on sustainability in senior design projects (Dancz, Ketchman et al. 2017 accepted); thus, I explored the demonstration of mastery of sustainability concepts in courses focused on sustainability, where it should be clearer to students that sustainability is the most critical element of the course. Application of a holistic sustainability rubric, developed by Dancz, Ketchman et al. (2017 accepted), was implemented to evaluate senior design through a mixed-methods approach. The major findings from the initial study highlighted the role of instructors and project rubrics in prompting students to incorporate sustainability to projects. Moreover, 86% of students' senior design projects did not meet ASCE BOK2 requirements for sustainability, attainment of Bloom's level "application." This research builds on the previous work and presents a comparative analysis, analyzing senior design and sustainable engineering course project results from the evaluative metrics integrated in the holistic sustainability rubric.

4.3.3.1 Holistic Sustainability Rubric

In the work of Dancz, Ketchman et al. (2017 accepted) a holistic sustainability rubric was developed to assess the sustainability content and student cognitive levels in senior design projects, but can be used to the same effect on any engineering course project. Extensive literature review led to the integration of three previously developed evaluative methods of student outcomes, namely *Bloom's Taxonomy*, Bielefeldt's *Dimensions of Sustainability*, and McCormick, Lawyer et al. *Sustainability Links* (Bloom, Engelhart et al. 1956, Bielefeldt 2013, McCormick, Lawyer et al. 2015). This rubric includes components from Bloom's, Bielefeldt, and McCormick, in addition to six metrics developed to further assess students' application and breadth in sustainability, including: 1) *Drivers for Including Sustainability* (e.g., client, student, rubric/instructor), 2) *Location of Sustainability Within Report* (e.g., independent section on sustainability versus integration throughout the report), 3) *Quantitative/Qualitative Incorporation,* 4) *Sustainability Source/Reference* (i.e., did projects cite sustainability resources), 5) *Sustainability Topics*, and 6) *NAE Grand Challenges of Engineering Topics*. For this research, however, *these six-additional metrics were streamlined to the three metrics: Quantitative/Qualitative Incorporation, Sustainability Topics*, and *NAE Grand Challenges of Engineering Topics*, for their applicability to the goal of this research, to assess dissimilarities in student outcomes and locate causality, in the context of sustainability.

Evaluating and coding of projects was performed on the sustainability content only; sustainability accounted for a portion of the senior design projects and the entirety of the stand-alone course projects. A comprehensive discussion detailing rationale for coding in each employed metric is provided in previous research (Dancz, Ketchman et al. 2017 accepted).

Bloom's Taxonomy rates students' intellectual contributions in six levels: knowledge, comprehension, application, analysis, synthesis, and evaluation (Bloom, Engelhart et al. 1956). Initially, projects were assessed to demonstrate knowledge in sustainability (i.e., recall of information), followed by the other five cognitive levels in sequential order, each as a precursor to the next level, following BOK2 standards: comprehension (i.e., explaining or summarizing material), application (i.e., use of quantitative methods, principles or laws), analysis (i.e., identification of relationships between material components), synthesis (i.e., proposal of new research), and evaluation (i.e., judging value of new information) (ASCE 2008).

Bielefeldt's *Dimensions of Sustainability* quantifies the times a pillar of sustainability (economic, environmental, and social) is discussed, categorized into four divisions: "no evidence" = no mention, "weak" = mentioned but no specific example, "fair" = mentioned one example, "good" = mentioned multiple examples (Bielefeldt 2013).

McCormick et al.'s *Sustainability Links* assesses incorporation of the relationships between the dimensions of sustainability integrated into projects, with three sequentially ordered categories: 1) "concept" for discussion of an individual sustainability topic, 2) "crosslink" for discussion of two sustainability topics as having effect and influence on each other, and 3) "interdependency" when all three pillars are discussed holistically within the project exemplifying the core idea of sustainability (McCormick, Lawyer et al. 2015). In developing the holistic assessment tool Dancz, Ketchman et al. (2017 accepted) synthesized *Sustainability Links* and *Dimensions of Sustainability*, requiring students to demonstrate "fair" or "good" discussion of sustainability before qualifying for "concept" in *Sustainability Links*.

The *Quantitative/Qualitative Incorporation* metric identifies students' qualitative (observed) and quantitative (measured) incorporation of sustainability. In *Sustainability Topics*, students' projects were assessed for explicit and implicit inclusion of topics in sustainability, intended to measure project breadth in sustainable engineering. A comprehensive list of 31 topics in sustainability, stemming from four core departments: climate, governance, infrastructure, and material was derived from students' curriculum in sustainable engineering courses at all participating universities for senior design and stand-alone courses. Similarly, projects were evaluated for explicit and implicit inclusion of topics from the fourteen identified NAE Grand Challenges of Engineering (*NAE Grand Challenges of Engineering Topics)* (NAE 2015).

4.3.4 Inter-relater reliability approach

Evaluation of course projects was completed by four graduate student researchers applying an Inter-Rater Reliability (IRR) approach. Implemented in evaluative research to ensure consistent and unbiased results, IRR is defined as a process where multiple evaluators, working independently, classify subjects or objects (Gwet 2014). Five steps were adapted for the course project evaluation process: 1) the team of three evaluators assessed a single project together, 2) the evaluators worked independently on a second project and discussed outcomes, 3) the evaluators were separately assigned a third project to assess before meeting to discuss outcomes, 4) the evaluators were randomly assigned the remaining course projects for assessment, and 5) the fourth evaluator assessed projects chosen at random to verify consistency of outcomes. These steps are designed to remove bias and inconsistency by aligning subjectivity of evaluators with proper interpretation of peer-reviewed evaluative methods. Each evaluator is considered an expert in sustainability topics; all four are mid to senior PhD students working on sustainable engineering research projects. Course projects were assigned to these evaluators randomly, evenly distributing projects by university, course, and year. Course instructors did not take part in the evaluation process for either course or senior design projects.

4.4 RESULTS AND DISCUSSION

This research aims to assess variation in students’ cognition of sustainability in senior design and sustainability-themed courses. The research does not aim to compare students’ cognition across stand-alone sustainability courses at two universities, thus, rather than presenting results for the two universities studied separately, results from both universities covering all semesters studied are aggregated into course and senior design totals, allowing for a straightforward comparison of students' cognition of sustainability demonstrated in course projects and senior design projects.

This section is organized by evaluative method, with results and discussion presented together. In-depth analysis of senior design results is discussed in prior research where examination of university-specific senior design outcomes in sustainability is performed (Dancz, Ketchman et al. 2017 accepted).

4.4.1 Bloom's taxonomy

Students' achievement of levels of *Bloom's Taxonomy* (Bloom, Engelhart et al. 1956) was assessed for sustainability content in the 85 stand-alone course projects and 43 senior design projects, illustrated in Figure 10. ASCE BOK2 utilizes *Bloom's Taxonomy*, establishing students' minimum cognitive achievement levels for a list of educational outcomes prior to practicing civil engineering as a profession, including sustainability. In sustainability, students are expected to reach Bloom's level of application by graduation, primarily measured in the senior design course. A primary requirement of "application" is the design of experiments (Bloom, Engelhart et al. 1956), and in the sustainability courses, students are taught about modeling resources and trained how to use them through in-class discussions and assignments. Further, rubrics for both sustainability courses include design-specific language, "*Present compelling results from testing*" and "*Describe the scope of your analysis and the method that you will use to test or address the green myth*." However, at the institutions examined, only 14% of senior design projects reached "application“ related to sustainability, while 28% of course projects reached "application" in the sustainability stand-alone courses. This suggests 86% of senior design projects do not, in the context of sustainability, meet the ASCE BOK2 requirements prior to practicing civil engineering, while stand-alone course projects perform slightly better, with 72% not meeting the BOK2 requirement of “application.”

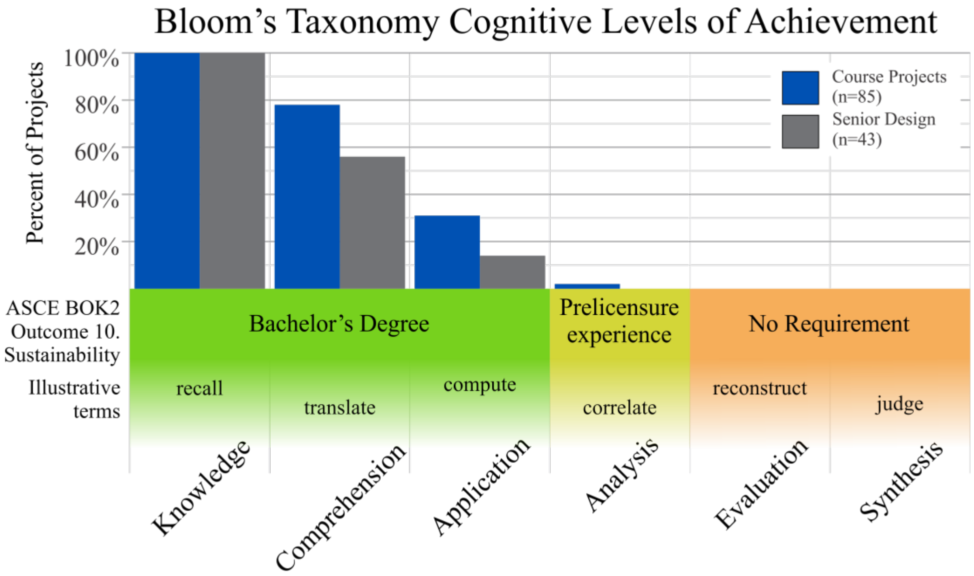


Figure 10. Bloom's Taxonomy (Bloom, Engelhart et al. 1956) resutls for course and senior design projects evaluating sustainability, including the ASCE BOK2 pre-requisites for students prior to practicing civil engineering professionally .

Evaluation was also done by assigning ordinal values for each of the six cognitive levels starting with knowledge (1), comprehension (2), application (3), analysis (4), synthesis (5), and evaluation (6). Results of a two-tailed Mann-Whitney U test with 95% confidence level, available in Appendix A section A.1, show the U-statistic from the sample population is less than the U-critical value (p-value = 0.005), leading to the rejection of the null hypothesis that the observations came from the same population. This test validates higher levels in cognitive outcomes for the stand-alone sustainable engineering course projects.

4.4.2 Dimensions of sustainability

Course and senior design projects were evaluated using Bielefeldt's *Dimensions of Sustainability* (Bielefeldt 2013) to determine which pillars of sustainability were incorporated in each project, and to what degree: "no evidence," "weak," "fair," or "good." This evaluation fulfills two essential roles: 1) evaluating projects' depth of discussion for each of the three pillars and 2) evaluating students' use of examples within the three pillars (environmental, economic, social). This evaluation provides a first insight to students' interests in sustainability at the pillar-level, before using other metrics to evaluate interconnectivity, topic specifics, and quantitative methods applied. Stand-alone and senior design project findings are illustrated in Figure 11.

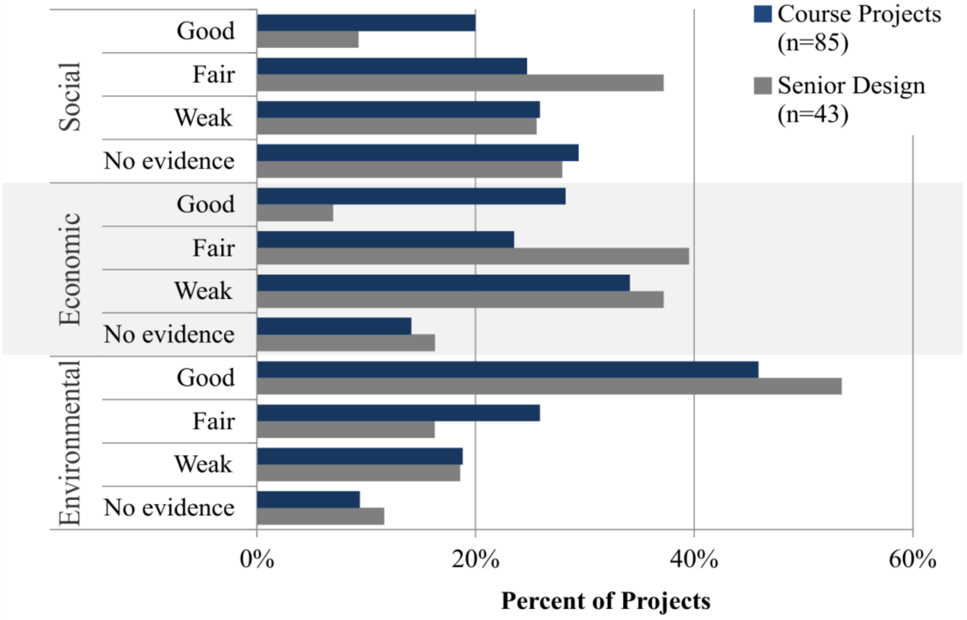


Figure 11. Summary of results in Dimensions of Sustainability (Bielefeldt 2013) for course and senior design projects, separated into the three dimensions of sustainability (Ketchman, Dancz et al. 2017).

Senior design and sustainable course projects paralleled each other in the environmental pillar, with the largest visible deviations occurring in the economic and social pillars. Stand-alone course projects noticeably reached "good" degrees of incorporation in economic (28% of projects) and social (20%) pillars more often than senior design, 7% and 9% respectively, potentially stemming from stand-alone sustainability course instructors exposing students to a variety of sustainability issues from each of the three pillars facing today's engineers.

It should be noted that only one project from both the course project group and senior design project group showed no evidence within all three dimensions; approximately 45% of projects from both courses incorporated elements from only a single dimension. Conversely, 56% of course projects and 53% of senior design projects incorporated aspects from all three pillars of sustainability.

A two-tailed Mann-Whitney U test, using a 95% confidence level, was performed, available in Appendix A section A.2, to compare student incorporation of sustainability by dimensions and cumulatively between senior design and stand-alone course projects. Ordinal values were assigned to each dimension as follows: no evidence (1), weak (2), fair (3), and good (4). It was determined that student incorporation of sustainability was not dissimilar enough to indicate a statistical difference in population samples for a given pillar: environment (p-value = 0.671), economic (0.165), social (0.772) or cumulative of the three pillars (0.369). This suggests no statistical difference in student outcomes for *Dimensions of Sustainability* between the examined senior design and stand-alone course projects.

4.4.3 Sustainability links

Sustainability Links based on McCormick et al. (McCormick, Lawyer et al. 2015) were adapted to assess project incorporation of sustainability and linkages between the three dimensions of sustainability coded in four divisions, “no evidence,” “concept,” “crosslink,” and “interdependency” shown in Figure 12.

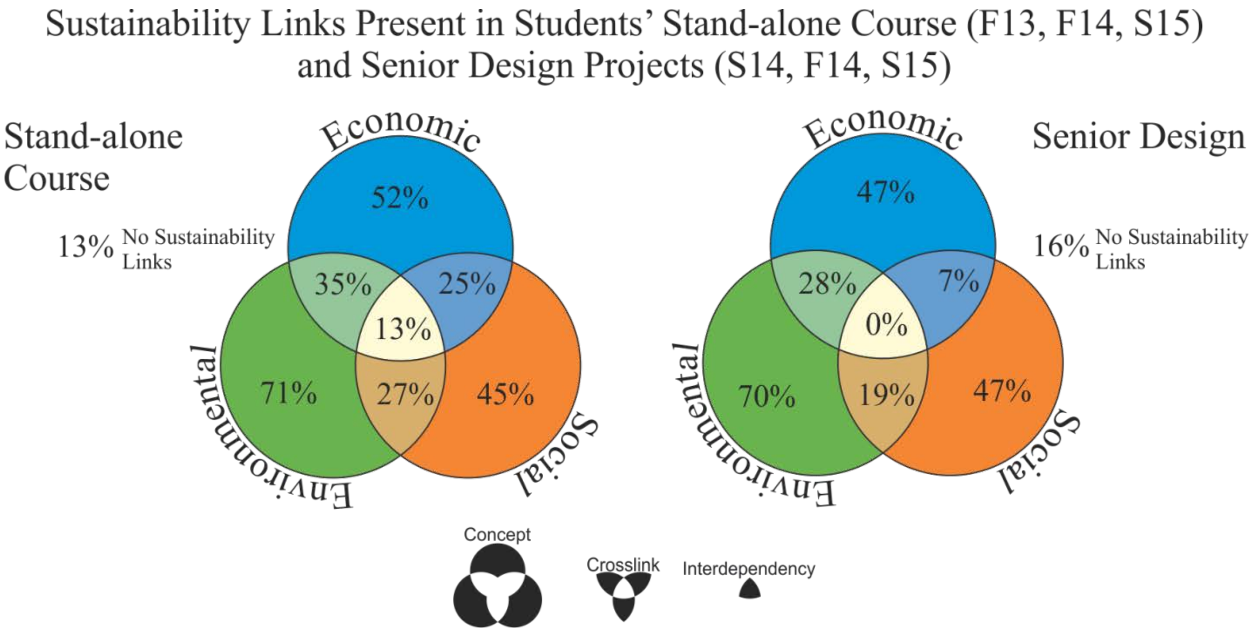


Figure 12. Illustration of Sustainability Linkage (McCormick, Lawyer et al. 2015) for the stand-alone course and senior design projects using the traditional Venn diagram of sustainability where “concept” is represented by the outer portion of each pillar of sustainability, “crosslink” is represented by the overlap of two pillars, and “interdependency” is the center of the diagram where all three pillars overlap, commonly defined as sustainability. Percentages do not add to 100%, because students’ projects may include any or none of the sustainability pillars at their discretion. [F13 is Fall 2013, S15 is Spring 2015, etc.] (Ketchman, Dancz et al. 2017)

Meeting “interdependency” criteria meant demonstrating comprehension of the relationship between all three pillars, and 11 course projects (13%) exhibited this level of understanding in contrast to zero senior design projects. Although, demonstration of interconnectivity-level thinking for stand-alone courses was not linked to higher levels of Bloom's cognition; 5 of 11 course projects reached "comprehension," 4 of 11 reached "application," and only 2 of 11 reached "analysis." However, those projects unable to go beyond recall of information (Bloom's initial cognitive level "knowledge") performed the weakest in *Sustainability Links;* 17 of 19 stand-alone course projects (11 of 19 senior design projects) demonstrated "no evidence" or concept-level thinking for only a single pillar. This demonstrates the need for students to have a deeper understanding of sustainability pillars before they are able to make relational connections between the pillars of sustainability.

Comparative analysis of sustainability linkage incorporated into the stand-alone sustainability course and senior design projects was performed using the two-tailed Mann-Whitney U test, with a 95% confidence level; results are available in Appendix A section A.3. Ordinal values were assigned to each of the four divisions in each pillar: no evidence (1), concept (2), crosslink (3), and interdependency (4). Results indicate significant difference between the senior design and stand-alone course populations (p-value = 0.012), suggesting students' course projects demonstrated an increase in levels of sustainability linkage incorporation. Most notably stand-alone course projects demonstrated improved levels of crosslink and interdependency incorporation.

4.4.4 Quantitative vs. qualitative

As engineers, students' ability to readily apply computational and experimental methods to determine appropriate solutions to problems was assessed in the *Quantitative vs. Qualitative* metric. Results are presented in Figure 13. Percentages are based on total projects evaluated meeting predetermined standards; projects must meet a minimum requirement of “weak” from *Dimensions of Sustainability* to be considered for qualitative or quantitative incorporation and inclusion of quantitative measures inferred qualitative incorporation.

Disparity in quantitative applications is visible between stand-alone and senior design projects. Overall, 70% of stand-alone course projects implemented quantitative measures in one or more pillars, in contrast to senior design projects demonstrating quantitative analysis in one or more pillars for only 16% of projects.

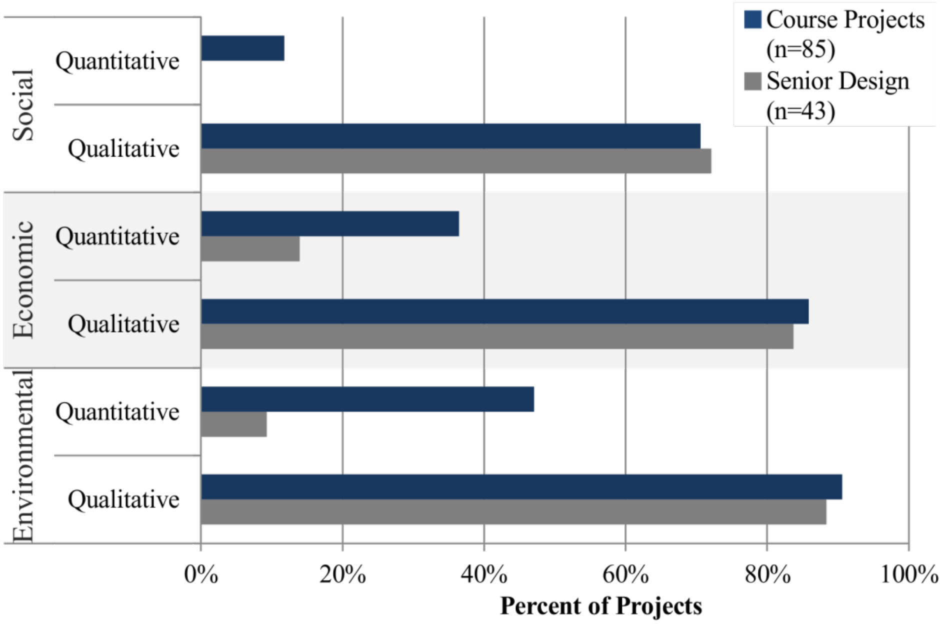


Figure 13. Quantitative versus qualitative inclusion of sustainability comparing course and senior design projects within each of the three pillars. Percentages are based on total projects evaluated for the stand-alone course and senior design projects, independently. Projects must meet a minimum requirement of “weak” from Dimensions of Sustainability (Bielefeldt 2013) to be considered for qualitative or quantitative incorporation and inclusion of quantitative measures inferred qualitative incorporation (Ketchman, Dancz et al. 2017).

Quantifiable measures in the environmental pillar included modeling efforts using peer-reviewed resources, e.g., the Argonne National Laboratory's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (Argonne National Laboratory 2011). Within the economic pillar, quantification required projects to rationalize economic calculations in terms of sustainability, typically by cost benefit analysis.

However, in the social pillar, neither course population performed particularly well with only 8% of total projects employing quantitative measures. This is understandable yet unfortunate given the state of social sustainability research in being able to quantify social implications accurately without marginalizing groups in the process. Most common was the end-point life cycle assessment, where students reported daily adjusted life-years (DALY) in results.

It is important to note that both universities participating in the senior design study require students, as part of their curriculum, to complete a sustainable engineering course, which exposes students to quantitative methods such as life cycle assessment and building energy modeling. However, senior design rubrics do not explicitly require students to include these quantitative methods for sustainable engineering design in contrast to the examined stand-alone course rubrics. The results suggest that rubric and instructor direction are pivotal to student outcomes, in the context of sustainability.

4.4.5 Sustainability topics

Sustainability topics were incorporated into the rubric to discern where students' were focusing their attention, by assessing implicit and explicit references within topic areas. These thirty-one topics surrounding the web graph in Figure 14 were derived from students' curriculum in sustainable engineering courses and are compartmentalized thematically: climate, governance, infrastructure, and material.

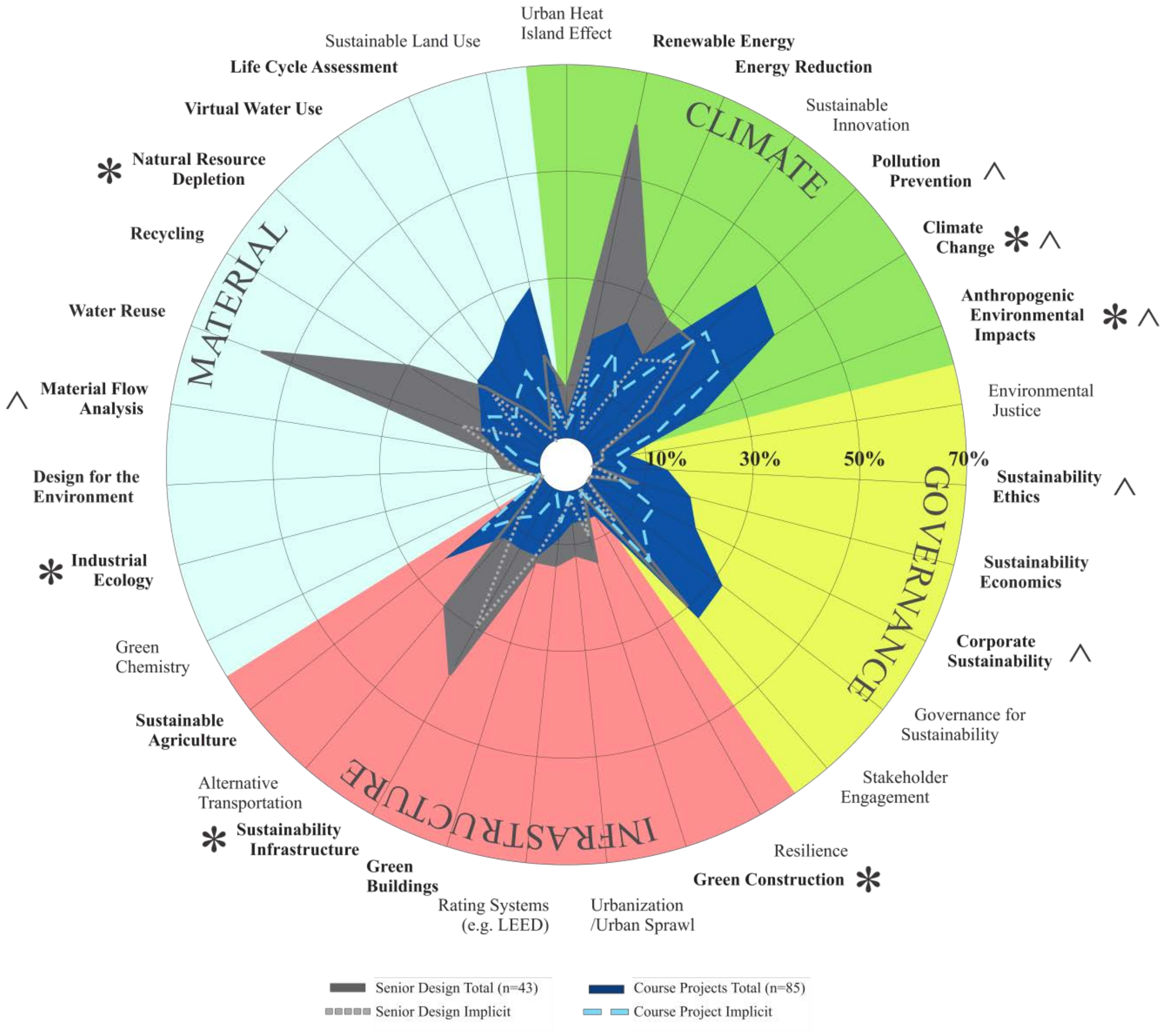


Figure 14. Distribution of course and senior design project inclusion for 31 sustainability topics, further categorized into implicit inclusion and total reference (implicit plus explicit inclusion). Topics in bold represent topics taught at one or both participating universities for senior design. (*) denotes class time dedicated to teaching a topic in ESD, while a caret (^) denotes class time dedicated to teaching a topic in ESEM (Ketchman, Dancz et al. 2017).

Explicit inclusion of sustainability in senior design projects primarily fell within six subcomponents: renewable energy (44% of projects), water reuse (40%), energy reduction

(30%), recycling (26%), alternative transportation (21%) and stakeholder engagement (21%) through international projects, accounting for nearly 70% of all explicit discussions of sustainability topics. In stand-alone course projects, 70% of explicit discussion was covered over twelve subcomponents with only 3 topics in common (*shown in italics*) with senior design results: pollution prevention (32% of projects), climate change (31%), *stakeholder engagement (18%)*, *energy reduction (18%)*, sustainable agriculture (16%), life cycle assessment (15%), , anthropogenic environmental impacts (14%), governance for sustainability (14%), corporate sustainability (13%), *recycling (12%)*, embedded/virtual water use (11%), and sustainable innovation (11%). A detailed accounting of implicit, explicit and total incorporation of sustainability topics is included in Appendix A section A.4.

The topics **excluded** from implicit or explicit discussion in senior design projects were notable, specifically *corporate sustainability*, *governance for sustainability*, and *sustainability ethics*; the CEE programs in the senior design group include course modules or stand-alone courses dedicated to some of the topics. For example, one university in the study requires students to take a course where half of the course is dedicated to *sustainability ethics*, yet this topic did not arise in senior design projects. However, course projects did reference these topics: *governance for sustainability* (32% of projects), *corporate sustainability* (22%), and s*ustainability ethics* (14%).

4.4.6 NAE grand challenges

Analysis of student projects from senior design and stand-alone sustainable engineering courses reveal similarities in the lack of awareness towards the NAE Grand Challenges (NAE 2015), illustrated in Figure 15; a detailed summary is provided in Appendix A section A.5. In both senior design and the stand-alone courses examined in this research, no projects explicitly discussed an NAE Grand Challenge, which required students to directly reference the NAE and specific challenge. Senior design projects, as expected, focused on “restore and improve urban infrastructure,” which aligns with traditional civil and environmental engineering foci and the projects primary attributes, including redesign of bridges and site development. Stand-alone projects were slightly more distributed throughout the topics considered to fall within traditional CEE concentrations. “Manage the nitrogen cycle” was most commonly referenced implicitly, stemming from students’ incorporation of *Sustainability Topics* within the climate department, specifically *anthropogenic environmental impacts*, *climate change*, and *pollution prevention*; two thirds of projects included at least one reference within these three topic areas. While inferences could be drawn that assume students are aware of the issues facing engineers, such as those posed by NAE Grand Challenges for Engineering (NAE 2015), it cannot be concluded if students are aware of the NAE Grand Challenges for Engineering themselves.

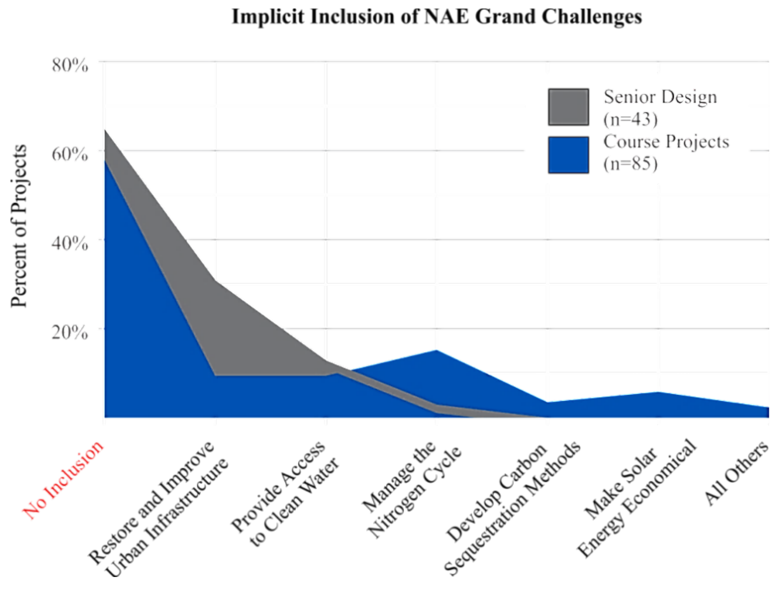


Figure 15. Distribution of implicit references within the NAE Grand Challenges (NAE 2015), including no inclusion. Note no projects included an explicit reference to any of the NAE Grand Challenges.

4.5 CONCLUSION

Senior design projects from Universities A and B, in addition to stand-alone course projects from Arizona State University and University of Pittsburgh were collected and evaluated using a holistic sustainability rubric, intended to assess student outcomes in sustainability. Statistical analysis revealed that the projects from the stand-alone sustainable engineering courses exhibited higher levels of cognition and increased linkage of the three pillars of sustainability. Further, it was observed that stand-alone course projects included a greater breadth of sustainability topics, over those projects from the senior design courses.

To provide additional guidance, I identified two possible reasons as to why students do not demonstrate greater knowledge of sustainability in senior design projects at University A and B: (1) a ‘packed’ or ‘full’ senior design course, and (2) expectations from instructors and rubrics may not contain clear elements of sustainability.

Senior design is intended to be a culminating “*major design experience based on the knowledge and skills acquired in earlier course work and incorporating appropriate engineering standards and multiple constraints*” (ABET 2015). Yet, it is my observation that senior design has defaulted (or has the potential to default) to a course where many ABET criteria are amassed. One outcome is what is observed in this research: lower levels of cognition for this studied area of sustainability. Contrary to expectations, because students are required to take a stand-alone sustainable engineering course prior to senior design, which this research demonstrates, students are capable of higher levels of cognition than presented in senior design projects.

It is postulated by that if senior design incorporated clearer expectations of sustainability, students’ sustainability learning outcomes may be higher. As illuminated in previous research on University A and B senior design courses, instructor expectations and project rubrics can guide sustainability integration into projects (Dancz, Ketchman et al. 2017 accepted). This is corroborated in this research, where sustainability focused instructors and detailed rubrics guided students whom exhibited higher cognition and deeper integration of sustainability, quantitatively and qualitatively, in stand-alone sustainable engineering courses.

Additionally, ASCE BOK2 (ASCE 2008) outlines cognitive outcomes for graduating seniors, including "application" levels in sustainability (outcome 10), but as observed in this research, students are capable of the higher cognitive level "analysis" when encouraged through instructor guidance and project rubrics. Moreover, integration of sustainable engineering to the foundation of civil and environmental engineering principles may result in students' incorporation of sustainability to design projects as a part of the natural course of design, without prompting through instructors or rubrics.

Future examinations should focus on longitudinal studies, applying the holistic sustainability rubric throughout multiple stand-alone sustainable engineering courses and following students through senior design. This level of study may elucidate indicators, other than those proposed in this research, that influence the incorporation or lack thereof, of sustainability within students' projects.

The findings of this research project reinforce the concept of using community interconnectedness to achieve energy reductions. Building on the findings of the flipped-class project, presented in Chapter 3.0, student outcomes demonstrate the potential incorporation of flipped-class pedagogies with stand-alone building science courses. Moreover, even though the NELC course is a stand-alone flipped-class course, the findings from this research project support the scaling up nationally of similar flipped-class sustainable engineering courses over incorporation of sustainable engineering lessons to senior design syllabi.

5.0 A SURVEY OF HOMEOWNERS' MOTIVATIONS FOR THE ADOPTION OF ENERGY EFFICIENCY MEASURES: EVALUATING A HOLISTIC ENERGY ASSESSMENT PROGRAM

This chapter addresses research question 2, *were the energy assessments and the proposed energy efficient measures effective in reducing residential energy consumption?* The research presented is a reproduction two articles: (1) conference proceedings for the International Conference on Sustainable Design, Engineering, and Construction published in *Procedia Engineering* and (2) an article under review in the *ASCE Journal of Architectural Engineering*.

(1) Ketchman, K.J., Riley, D., Khanna, V., Bilec, M.M. (2016). "Evaluation of Holistic Energy Assessment Program." International Conference on Sustainable Design, Engineering, and Construction, May 18-20, 2016, Tempe, Arizona. Procedia Engineering, 145, 468-475. doi:http://dx.doi.org/10.1016/j.proeng.2016.04.020

(2) Ketchman, K. J., Riley, D., Khanna, V., and Bilec, M. M. (2017 submitted). "A Survey of Homeowners' Motivations for the Adoption of Energy Efficiency Measures: Evaluating a Holistic Energy Assessment Program." Submitted, ASCE Journal of Architectural Engineering.

5.1 INTRODUCTION

Residential buildings accounted for over one fifth of U.S. primary energy consumption in 2015, with single-family homes constituting 80% of the sector's energy consumption (U.S. EIA 2009, U.S. EIA 2012). Efforts to curtail demand-side energy consumption have included key U.S. energy policy spanning multiple decades, such as the National Appliance Energy Conservation Act of 1987, Energy Policy Act of 1992 and recently the Energy Efficiency Improvement Act of 2015 (S. 83 - 100th Congress 1987, H.R.776 - 102nd Congress 1992, S. 535 - 114th Congress 2015). These policies have helped shape the appliance efficiency market by mandating increasingly rigorous efficiency standards for a growing portfolio of appliances, in part assisting the sale of over an estimated two billion Energy Star certified appliances, a benchmark for high efficiency appliances (U.S. EPA 2012). However, efficiency standards can only go so far to reduce energy consumption, leaving homeowners with the choice to adopt energy efficiency measures.

One approach to address demand-side energy conservation in the built environment is the energy audit. Regularly integrated to energy conservation programs as a strategy of curbing demand-side energy consumption, energy audits are designed to inform and guide homeowners' in their energy efficiency improvements (Abrahamse, Steg et al. 2005). Moreover, research has shown that tailored information is more effective in disseminating energy efficiency information than mass media campaigns, pointing towards the benefits of an energy audit over other engagement strategies (Abrahamse, Steg et al. 2005, Steg 2008, Fuller, Kunkel et al. 2010, Murphy 2014). However, the efficacy of traditional energy audits to lower household energy consumption has been questioned, with researchers postulating the cost-savings oriented energy audit as inadequately addressing homeowners' holistic motivations to adoption of energy efficient technologies (Ingle, Moezzi et al. 2012, Frondel and Vance 2013, Murphy 2014). In summary, the efficacy of energy audits, while seemingly promising, is mixed.

In response, the National Energy Leadership Corps (NELC) was developed and implemented with the intent of educating and training college-level students in holistic energy assessment strategies and leadership, along with systems-thinking and building energy processes. The NELC designed a holistic energy assessment approach, centered around consumer energy segmentations following Gravesian worldviews (Shelton Group and Worldview Thinking 2011), to address the heterogeneous nature of homeowners' behaviors and the varying motivators that drive energy efficiency investments. For example, the worldview "true believer" may apply to someone with intrinsic motivators including the environment and social responsibility. Conversely, the "working class realist" may only exhibit intrinsic motivators centered on saving money.

To evaluate the efficacy of the NELC program, a post-assessment survey was developed and distributed to 82 households that participated in a NELC holistic energy assessment (Ketchman, Riley et al. 2016). The survey focused on homeowner adoption of recommended energy efficiency improvements, perceptions on motivations to adopt, and catalytic impacts of the energy assessment. Catalytic impacts are defined as additional investments in energy efficiency measures outside of those improvements recommended to homeowners. Statistical analysis of survey responses was conducted.

In the following section, a review of energy audits in the residential sector followed by the case for holistic energy assessments is presented. In section 5.3, the NELC background and assessment process is discussed, in addition to presenting the survey design and statistical methods adopted for analysis. The efficacy of the NELC program is assessed via the statistical results gleaned from the survey. Finally, recommendations to aid energy conservation program and policy design and building energy research are presented.

5.2 RESIDENTIAL ENERGY AUDITS

Information strategies are widely incorporated to demand-side energy conservation programs relying on the principle that education will lead to change, and include mass media campaigns, smart meters, and energy audits. Energy audits, defined as *antecedent* (Abrahamse, Steg et al. 2005) information strategies, attempt to educate homeowners prior to purchasing energy efficiency improvements. Audits are commonly adopted to energy conservation programs strategic plans, in part because research has shown that tailored information is a more effective tool for promoting energy efficiency mass media campaigns relying on generalized information (Abrahamse, Steg et al. 2005, Steg 2008, Murphy 2014).

American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) defines three levels of energy audits, starting at *Level I* with visual inspection of the building and energy bills and progressively becoming more intensive (Pe and Pe 2011). A *Level II* energy audit collects field data, analyzes energy bills, and includes discussions with building owners and occupants; *Level III* includes advanced field data collection (e.g. blower door testing) and rigorous energy analysis using building modeling software. *Level III* audits are intended to identify comprehensive deep energy reductions, and depending on the scope of work may be beyond the needs or means of homeowners. The NELC energy assessment falls between a *Level II* and *Level III* audit, deploying visual inspection, infrared thermography, and energy bill analysis, stressing the importance to informal discussions with homeowners; detail of the NELC holistic energy assessment is discussed in the *Methods* section.

A comprehensive study conducted by Fuller, Kunkel et al. (2010) evaluated fourteen energy improvement programs located throughout the United States. While the study was performed at the program level, most programs included an energy assessment acting as the primary pathway for information between homeowner and professionals. Conclusions on key successful aspects of the programs are uncertain, because many programs did not report household engagement or track household energy savings. Although, programs tracking household energy improvements showed an average annual electricity saving ranging between 12 and 17%, a range that would save between 570 to 820 trillion Btu annually, if extrapolated on a national scale (U.S. EIA 2012). Research examining the efficacy of energy audits in the residential sector has been published, with a representative sample subsequently following this section.

5.2.1 Energy audit efficacy and homeowner heterogeneity

Through a national survey of homeowners receiving energy audits in the Netherlands, Murphy (2014) examined the influence of energy audits on homeowners' energy efficiency adoption rates and attempted to resolve reasoning for these rates. The energy audit implemented for this research followed Netherlands national standards (BRL 9500), requiring a comprehensive energy report focused on energy use and possible savings. From 3,737 respondents receiving an energy audit, only 19% stated the energy audit was influential in their decision to invest in energy efficiency. Further, when comparing against a control group, survey results show over 60% in both groups (those who received and did not receive an energy audit) had invested in energy efficiency measures, suggesting a lack of influence of energy audits.

Through comparison of survey results and dwelling characteristics (e.g. age, type), Murphy (2014) concludes homeowners make energy retrofit decisions based on *perceptions of comfort over the technical information* provided through an energy audit, a finding supported by others (Barr, Gilg et al. 2005, Bruel and Hoekstra 2005, Ingle, Moezzi et al. 2012, Ingle, Moezzi et al. 2012). Adding that homeowners knowingly incur higher energy bills in order to maintain a level of comfort deemed cost worthy, contrary to traditional thinking of financial motivators being most important to homeowners.

Other factors influencing energy investments have been identified, including socioeconomic status (Bruel and Hoekstra 2005), homeowner perceptions (Barr, Gilg et al. 2005), and homeowner expectations (Frondel and Vance 2013). Kastner and Stern (2015) provide a review of behavioral research looking in part at homeowners' dispositions and beliefs. Bruel and Hoekstra (2005) observed the role of socioeconomic status on energy efficiency improvements, finding that economically disadvantaged populations were motivated by subsidies, while wealthier populations were motivated by comfort and societal responsibilities. A paper by Barr, Gilg et al. (2005) found perception-based factors, such as responsibility for personal energy use and self-presentation, factored into energy behaviors of survey respondents. Ingle, Moezzi et al. (2012) suggested homeowners' perception of hassle of retrofit implementation and risk or uncertainty of energy savings played a role in retrofit investment by homeowners.

Frondel and Vance (2013) examined heterogeneity in homeowner responsiveness to energy audits, finding that homeowner expectations influenced their participation in energy efficiency improvements. In general, the audit may discourage optimistic homeowners from investing in energy improvements if the energy audit did not meet homeowner expectations of net benefits to investing in the improvement, and vice versa for pessimistic homeowners. Further, research identifying the role of socioeconomic indicators and housing characteristics has been performed, resulting in linkage between energy efficiency investments and income, education, and age of household members, and age of housing units (Nair, Gustavsson et al. 2010, Martinsson, Lundqvist et al. 2011, Gamtessa 2013, Achtnicht and Madlener 2014, Kastner and Stern 2015). While research has identified an array of potential factors to homeowner energy efficiency investment rates, research exploring holistic energy audit approaches is lacking; although, research has identified the need for increased personalization of energy audits.

Fuller, Kunkel et al. (2010) outline ten *key lessons for energy program designers*, with several lessons advising personalization of information and the audit experience, notably the application of behavioral sciences and identification of target audiences' motivations and barriers. Employment of these lessons to energy audits advocates for further personalization and tailoring of information, beyond the traditional financial scope of energy audits. In support, Ingle, Moezzi et al. (2012) recognized the possibilities of an energy auditor as a pathway to personal energy recommendations that leverage the inherent attributes of retrofits (e.g. comfort, hassle, uncertainty of savings) with homeowner interests and concerns (e.g. budget to spend on retrofits, satisfaction in thermal comfort, desire to update appliances and priority of home investments). Further, a study by Wilson, Crane et al. (2015) explores homeowners' behaviors and energy efficiency policy, suggesting that energy incentives should be designed within the context of homeowners' domestic lives. Review of the literature presents a strong case for holistic approaches, and acts as the basis for this research focusing on holistic energy assessments and guiding future program design.

5.3 METHODS

In this section an overview of the NELC program and homeowner engagement strategies is presented. A description of the energy assessment process including worldview segmentation is outlined, preceding a detailed discussion on the survey design and implementation.

5.3.1 The NELC program

The National Energy Leadership Corps is intended to teach students about leadership, home energy efficiency, and empower them to conduct home energy assessments in their community. The design of the program reflects the need for alternative models to personally engage homeowners in a holistic approach to home energy concepts, and also respond to the limitations of traditional professional home energy audit processes that are focused on motivating homeowners to invest in home energy improvements (Riley, Whelton et al. 2012).

5.3.2 Homeowner recruitment

Several strategies were employed to recruit homeowners in the Pittsburgh, Pennsylvania community, including collaboration with neighborhood community associations and advertising through electronic mailing lists. At community meetings, a brief presentation on the NELC program and energy assessment process was provided along with pamphlets and the opportunity to sign-up for an energy assessment. Emails included the pamphlet in combination with a web-site (http://sustainability.psu.edu/nelc) where homeowners could sign-up for an energy assessment. Not all households were eligible, as part of the NELC program design. Household eligibility required: single-family, detached homes, owned by the occupants. This intended to reduce specific barriers to energy efficiency (e.g. split-incentive) and address the largest housing unit type; 55% of all U.S. residential buildings (U.S. EIA 2009).

5.3.3 The NELC Holistic Energy Assessment

The NELC holistic energy assessment approach intends to: (1) maintain a worldview-neutral approach to avoid alienating homeowners with strong values and tendencies, (2) adapt recommendations based on worldview, interests, and energy concerns of the homeowner, and (3) modify report style based on variable cognitive styles and worldviews of homeowners (Sprehn, Whelton et al. 2015).

Students participate in a semester long course training them to conduct the NELC holistic energy assessment including: visual inspection, infrared thermography, a homeowner survey to determine worldview, energy bill analysis, and end-use energy disaggregation methods. Students are trained to communicate with homeowners effectively and without bias, aimed at gauging a homeowner’s energy awareness and personal motivators to investing in energy improvements. The intended outcome of an NELC assessment is a report tailored to a homeowner’s identified worldview, as defined by Shelton Group and Worldview Thinking (2011), and motivations for investing in energy retrofits.

5.3.3.1 Consumer Energy Segmentation

Consumer energy segments were defined through a Shelton Group survey of 1,459 respondents employing a factor analysis method and aligning with Gravesian worldviews (Roberts 2008, Shelton Group and Worldview Thinking 2011). The study identified four segmentations: cautious conservatives, working class realists, concerned moms, and true believers. These groups have delineated worldviews and motivations; although, there is overlap in motivations and the Shelton Group acknowledges that an individual may move between worldviews throughout the course of a day. Figure 16 illustrates each segment's share of population and summarizes extrinsic and intrinsic motivations. Using information obtained through the energy assessment process, delivered reports were aligned with homeowners' identified worldviews and accompanying motivators, enabling a deeper more personal energy report intended to improve adoption rates of recommended energy efficiency measures.

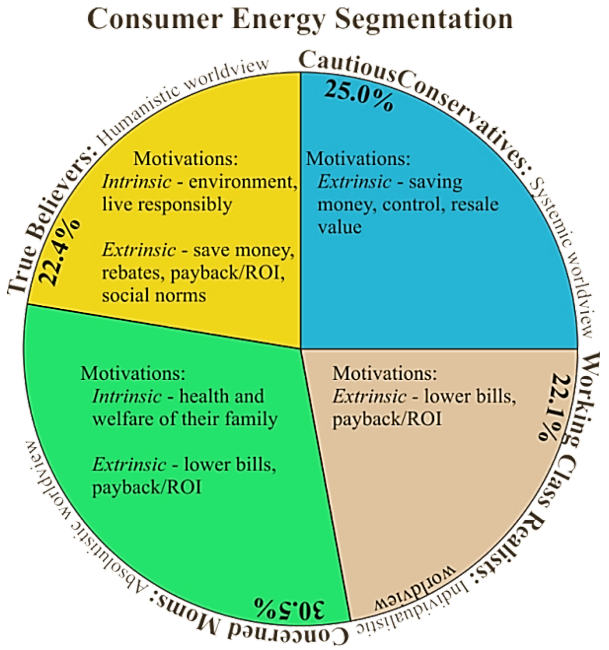


Figure 16. Shelton Group survey results summarizing consumer energy segmentation market share and motivations for investing in energy efficiency improvements (Shelton Group and Worldview Thinking 2011).

5.3.3.2 On-site Energy Assessment Process

The holistic energy assessment has three steps: (1) sit-down survey (e.g., kitchen table talk), (2) site/home walkthrough and data collection, (3) energy analysis and report writing, along with report delivery and follow up. The sit-down survey is designed to collect initial building information such as age, state of renovations, and homeowner perceived problem areas, in addition to general mechanical system information (e.g. age of equipment and fuel source). Further, the survey inquires to homeowners' interests in energy efficiency improvements starting with direct-install options and moving towards more comprehensive monitoring and control and site-generation of renewable energy. This enables students to evaluate and recommended personalized energy improvements in consideration with a homeowner's stated interests, concerns and worldview, e.g. one homeowner indicated an explicit dislike of compact fluorescent bulbs' aesthetics, leading students to recommend an LED option.

The second step is a walk-through of the home's exterior and interior to collect the pertinent building information, such as mechanical systems and appliances. Students utilize a package of tools, including but not limited to an infrared thermography camera and web-based application streamlining data collection, which students are trained to use throughout the course. In one instance, utilizing the infrared camera students were able to identify possible mold growth behind a vinyl-clad wall (Figure 17A), disjointed air ducts behind an interior wall (Figure 17B), and locations with inadequate insulation (Figure 17C). One group of students applied the thermography in a novel manner looking at the water heater flue for improper ventilation of combustion gases; illustrated in Figure 17D, combustion gases are visible as a fog-like cloud surrounding the flue vent opening. In addition to visual inspection of the building, students also conduct informal discussions as a means of disseminating building science information, such as thermal conduction at uninsulated walls, and to further identify homeowner interests of potential energy efficiency recommendations. Lastly, students collect energy bills for use in the energy analysis process.

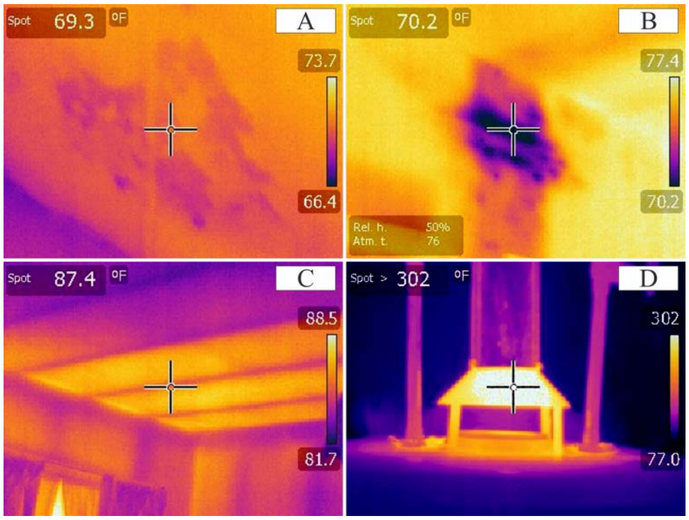


Figure 17. Infrared images captured by students during on-site residential energy assessment walkthroughs, depicting possible mold growth behind a vinyl-clad wall (A), a disjointed air duct behind an interior wall (B), inadequate attic insulation behind a knee-wall (C), and improper ventilation of combustion gases at a water heater flue vent (D) (Ketchman, Riley et al. 2017 submitted).

The third step of the assessment process includes energy analysis and report writing. Students apply the Krigger and Dorsi (2009) energy bill disaggregation method in determining energy consumption in four end-uses: heating, cooling, water heating, and base electrical load. A list of energy resources was catalogued for use in the students' energy analysis; for example, the U.S. DOE has made available energy retrofit calculators for many common appliances, mechanical systems, and lighting choices (U.S. DOE 2014). Students were directed to choose ten potential energy efficiency measures, suited to their energy assessment, and calculate potential savings for each measure. From these ten, a *prioritized list* of the top five energy efficiency measures (EEM) was amended to the energy assessment report for delivery to the homeowner. The prioritization of EEMs was based on several factors, including homeowner worldview, homeowner interests, building safety needs, energy and financial savings, and perceived costs to implement.

The report appearance has changed since the first iteration in 2012, but has maintained the same educational design, aimed at educating homeowners through defining and advising on the cause and remedy of the energy issues seen during the walk-through (Sprehn, Whelton et al. 2015).

Oversight by an instructor and teaching assistant focused on the validity of student-derived energy improvements, ensuring homeowners received appropriate energy efficiency recommendations; although, corrections to students reports commonly focused on cost savings. Students also submitted a technical document, containing calculations and assumptions, and a first draft of the assessment report for review and approval by the instructor and teaching assistant prior to mailing a physical copy of the final report to the homeowner.

5.4 POST-ASSESSMENT HOMEOWNER SURVEY

To assess the performance of the NELC program, a survey was developed and launched, through email, in May 2015 using Qualtrics software (Qualtrics 2015). Since 2012, a total of 120 homeowners have received an energy assessment through the NELC program. Eligibility for participation in the survey required a valid email address, and 9 months since receiving the energy assessment. Ingle, Moezzi et al. (2012) found that it took homeowners less than 12 months to implement at least one energy retrofit. Removal of spring 2015 energy assessments and homeowners without a valid email address left 82 possible participants. Emails containing a link to the survey were sent every other week for 10 weeks. A total of 27 homeowners responded with representation from all possible assessment periods with a response rate of 33%, illustrated in Table 8. Survey participants had the choice to skip questions. Anonymous and synchronized coding of energy assessment documents with homeowner surveys maintained anonymity and provided comparative data sets. This research received IRB exempt approval (Approval # PRO15030578).

Table 8. Distribution of residential energy assessments and survey respondents by assessment period. Note, (a) no valid emails for summer 2012 participants, (b) spring 2015 occurred within 9 months of the survey (Ketchman, Riley et al. 2017 submitted).

Assessment Period	Number of Homes Assessed	Number of Homes Receiving Survey	Number of Survey Respondents	Response Rate	Months Since Assessment
Spring 2012	13	10	5	50%	36
Summer 2012[a]	7	0	0	-	33
Spring 2013	9	7	5	71%	24
Summer 2013	49	36	6	17%	21
Spring 2014	12	12	7	58%	12
Summer 2014	19	17	4	24%	9
Spring 2015[b]	11	0	0	-	0
Totals	120	82	27	33%	

5.4.1 Nomenclature

The organization of the energy efficiency measures recommended to homeowners is important in the discussion of survey results and design, presented below. Each participating household received an energy assessment report which contains at most five energy efficiency measures

(EEMs) recommended for investment. The recommended EEMs are prioritized according to worldview and need as identified by student assessors, but homeowners are not explicitly directed to adopt the EEMs in the posed order. Table 9 presents a full list of the EEM constructs.

Table 9. A summary list of the energy efficiency measure (EEM) constructs. Column headings are the six aggregated groupings with the associated subgroups listed below. The 21 subgroups also represent the choices available to homeowners in section two of the survey inquiring about catalytic impacts of the NELC home energy assessment.

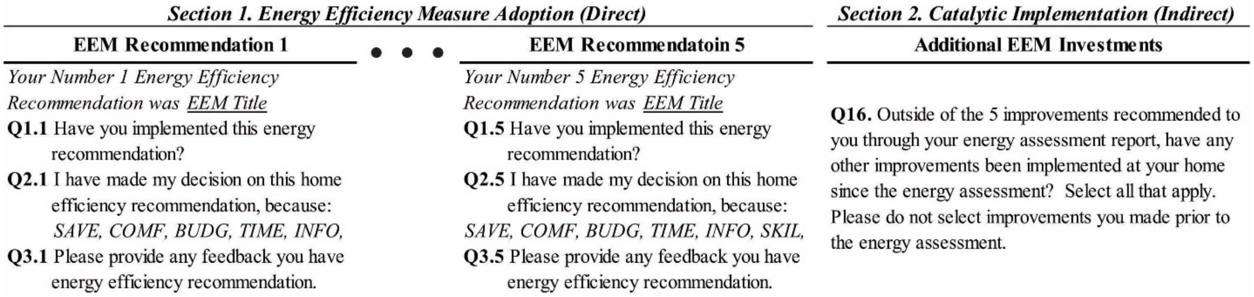
Appliances	Envelope	HVAC	Lighting	Water Heating and Water Reduction	Other Improvements
Major appliances	Insulation	Air ducts	Lighting	Water heater	Carbon monoxide detectors
Power strips	Repointed brick	Central air conditioner		Water heater insulation	Home energy management system
	Weatherization	Ductless air conditioner		Water reduction	On-site renewable energy
	Windows	Primary heating source			Purchase 'green' energy from a utility
		Programmable thermostat			Smoke detectors
		Whole house fan			

For the purpose of statistical analysis, all EEMs are categorized into two constructs: EEM aggregated groups (*EEMagg*) and EEM subgroups (*EEMsub*). The EEMagg groups are six representative collections of similar energy improvements, and are labeled as *appliances*, *envelope*, *HVAC*, *lighting*, *water heating and water reduction*, and *other improvements*. The EEMsub construct breaks down the EEMagg into 21 more specific types of improvement, such as upgrading the primary heating source. Within an EEMsub there is potential for further disaggregation (e.g. upgrade primary heating source includes boilers, forced air blower, or air source heat pumps); although, sample sizes from survey responses correspondingly become smaller as EEM groups are disaggregated. It should be noted that the 21 EEMsub groups were also used in section two of the survey inquiring about catalytic impacts from the NELC home energy assessment.

5.4.2 Survey design

The survey is composed of two sections consisting of multiple-choice and Likert scale questions. The first survey section addresses the energy efficiency measures recommended specifically to the homeowner through the energy assessment report, and is titled *Energy Efficiency Measure Adoption (Direct)* in Figure 18. The second section assesses additional EEM investments by the homeowner, if any, outside of those recommended in the energy assessment report, and is labeled *Catalytic Implementation (Indirect).* Since observed investments were made outside of the recommendations, it was important to recognize these efforts as well. The terms *adoption* and *implementation* are important, as *adoption* refers to the investment in an NELC recommended EEM. *Implementation* refers to a homeowner-identified and invested energy efficiency measure, and is potentially a part of an indirect, or catalytic, effect of the NELC home energy assessment.

This first survey section aimed to understand the effectiveness of the NELC holistic approach by evaluating: adoption rates, type of EEMs adopted (i.e. comprehensive versus direct-install, or building envelope versus lighting), and homeowner perceptions on their motivations to investing, or not, in the recommended EEMs. For each EEM, a homeowner is asked, “Have you implemented this energy efficiency recommendation,” with five possible responses: 1) yes, I have done it, 2) I will do it in the next month, 3) I will do it in the next year, 4) I do not anticipate ever making this improvement, and 5) I am uncertain.



Section 1. Energy Efficiency Measure Adoption (Direct)

EEM Recommendation 1

Your Number 1 Energy Efficiency Recommendation was *EEM Title*

Q1.1 Have you implemented this energy recommendation?

Q2.1 I have made my decision on this home efficiency recommendation, because: *SAVE, COMF, BUDG, TIME, INFO,*

Q3.1 Please provide any feedback you have energy efficiency recommendation.

• • •

EEM Recommendatoin 5

Your Number 5 Energy Efficiency Recommendation was *EEM Title*

Q1.5 Have you implemented this energy recommendation?

Q2.5 I have made my decision on this home efficiency recommendation, because: *SAVE, COMF, BUDG, TIME, INFO, SKIL,*

Q3.5 Please provide any feedback you have energy efficiency recommendation.

Section 2. Catalytic Implementation (Indirect)

Additional EEM Investments

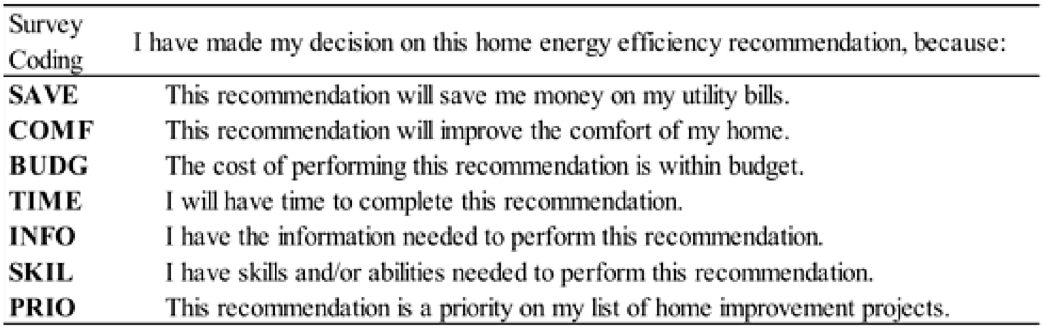
Q16. Outside of the 5 improvements recommended to you through your energy assessment report, have any other improvements been implemented at your home since the energy assessment? Select all that apply. Please do not select improvements you made prior to the energy assessment.

Figure 18. Survey design illustrating two sections and question content.

Note for brevity: SAVE - This recommendation will save me money on my utility bills,
COMF - This recommendation will improve the comfort of my home,
BUDG - The cost of performing this recommendation is within budget,
TIME - I will have time to complete this recommendation,
INFO - I have the information needed to perform this recommendation,
SKIL - I have skills and/or abilities needed to perform this recommendation,
PRIO - This recommendation is a priority on my list of home improvement projects.

A series of follow up questions on possible motivators to energy efficiency investments prompted homeowners to answer seven Likert scale questions starting with the statement, “I have made my decision on this home energy efficiency recommendation, because….” Responses were worded positively to avoid confusion by homeowners participating in the survey, and respondents could choose from *strongly disagree*, *disagree*, *agree*, or *strongly agree*, see Figure 19 for the list of motivator questions. A neutral option was omitted from survey design to avoid satisficing, encouraging participants to think intently in that way offering meaningful opinions (Krosnick, Holbrook et al. 2002).

The second survey section assesses catalytic impacts of the energy assessment, asking if a homeowner undertook any additional energy efficiency measures outside of those recommended by the energy assessment report since receiving their energy assessment. A list of the 21 EEMsub, from which homeowners could select as having implemented are outlined in the aforementioned Table 9. The improvements identified by homeowners in this section as being *implemented* since the energy assessment potentially originated from the on-site energy assessment where students engage homeowners in open discussions and provide educational energy information.



Survey Coding	I have made my decision on this home energy efficiency recommendation, because:
SAVE	This recommendation will save me money on my utility bills.
COMF	This recommendation will improve the comfort of my home.
BUDG	The cost of performing this recommendation is within budget.
TIME	I will have time to complete this recommendation.
INFO	I have the information needed to perform this recommendation.
SKIL	I have skills and/or abilities needed to perform this recommendation.
PRIO	This recommendation is a priority on my list of home improvement projects.

Figure 19. Survey questions on motivators for each energy efficiency recommendation. Each question could be answered: strongly disagree, disagree, agree, or strongly agree. Note: the column "Survey Coding" was not a part of the survey and is used only for reference in this research.

5.4.3 Statistical methods

To evaluate the efficacy of the NELC holistic energy assessment approach, two statistical tests were implemented: a two-sample hypothesis test on the difference in population proportions and chi-square test for independence using contingency tables. A combination of the statistical methods provided insight to the relationship between recommended EEMs, homeowners' likelihood to adopt, and perceptions of motivators on the decision to adopt an EEM.

5.4.3.1 Organization of Survey Responses

Responses were sorted according to the EEMagg group (e.g., Appliances, envelope) providing context to results, such as understanding potential barriers to adoption for a specific EEMagg. Sample sizes varied for each EEMagg, dependent on number of EEMs recommended to a household and homeowners' full participation in answering all survey questions. This led to the omission of EEMagg *appliances*, *lighting* and *other improvements* from all statistical testing, because their sample sizes were too small and each group could not be added to other EEMagg groups. However, homeowner response data are presented for these EEMagg without statistical analysis.

Some homeowners received multiple EEMs within an EEMagg group. Given the relatively small sample sizes within each EEMagg, a homeowner receiving multiple EEMs within an EEMagg could potentially skew results. Although, the individual EEMs recommended to any homeowner were distinctly different by specificity of the recommendation and by the varying degrees of demands and challenges to realization of the EEM. For instance, one homeowner was recommended to install insulation in three locations, at the attic knee wall, in partially exposed basement exterior walls, and at the rim joist. In this instance, each recommendation differs in specificity and barriers to adoption (e.g. accessibility to behind walls), and these barriers were exemplified by the homeowners' varying survey responses to the three EEMs.

5.4.3.2 Binomial Transformation of Data

The statistical tests required transformation of the categorical responses into binomial data. Responses to the question of EEM adoption from section one of the survey were assigned binomial values according to whether or not the EEM had been implemented. A response of "yes, I have done it" was assigned a value of one associated with an occurrence of an event (i.e. adoption of the EEM). All other responses were assigned a value of zero representing a non-occurrence; participants had a minimum of nine months to adopt the EEM prior to the survey.

Transformation of Likert-scale motivator questions followed a similar approach. An "event" was defined as a positive perception with responses, *agree* and *strongly agree*, assigned a value of one, and negative responses, *strongly disagree* and *disagree*, assigned a value of zero.

5.4.3.3 Two-sample hypothesis test on the difference in proportions

A two-sample hypothesis test on the difference in proportions was selected to analyze relationships between: (1) adoption rates and homeowners' perceptions of motivators for their decision on adoption of an NELC recommended EEM, and (2) homeowners' perceptions of EEMs they chose to adopt in comparison to perceptions of EEMs they chose not to adopt. In comparing adoption rates with homeowner perceptions, two-tailed and upper-tailed hypothesis tests were constructed under a 95% confidence level and null hypothesized difference in proportions equal to zero. The alternative hypothesis for the two-tailed test was set with the difference in proportions not equal to zero, and for the upper-tailed test, the proportion of EEMs adopted was less than proportion of positive responses to motivator questions.

A p-value less than 0.05 rejects the null hypothesis confirming the proportions of adopted EEMs and homeowner responses are statistically different (two-tail test), with the proportion of homeowners responses greater than the proportion of adopted EEMs (upper-tailed test). However, failure to reject the null hypothesis (p-value greater than 0.05) arises when homeowners have a less positive perception of a motivator, and correspondingly low adoption rates. The result of a p-value greater than 0.05 suggests the motivator may have acted as a barrier to adoption. The combination of the tests results provide insight to correlation between motivators and EEMs

Hypothesis testing was performed comparing homeowners' perceptions for those EEMs adopted against non-adopted EEMs. Homeowners potentially contribute to both categories, adopted and non-adopted, as they choose to adopt one EEM and reject another. Only two-tailed tests were performed for the difference in perceptions of adopters versus non-adopters, to evaluate if the samples differed.

5.4.3.4 Contingency tables

Contingency tables display frequency distributions of multivariate observations, and are useful in testing for dependency of variables using the Chi-square test for independence. Chi-square tests (χ^2) were constructed using a 95% confidence level and one degree of freedom, inherent to a 2x2 contingency table. The null hypothesis of a χ^2 test is independence of variables. Rejection of the null hypothesis suggests a relationship between the variables.

Survey responses were again categorized into the four EEMagg groupings with adequate sample sizes, and contingency tables were constructed using the binomial data for EEM adoption and motivator perception. For the four EEMagg groups, *appliances*, *envelope*, *HVAC*, and *water heating and water reduction*, a contingency table was created for each of the seven *motivator* questions asked in the survey, identified as: SAVE, COMF, BUDG, TIME, INFO, SKIL, and PRIO. A total of 28 contingency tables and chi-square tests were performed.

5.5 RESULTS & DISCUSSION

In this section, key findings from the survey are outlined accompanied by supporting statistical evidence. First, results of two-sample hypothesis tests are evaluated, where homeowners' perceptions to motivator questions and corresponding adoption of the EEM are examined to identify correlation, in particular where homeowner perception acts as a barrier to adoption. This is followed by organization of survey responses into those associated with EEMs adopted and not adopted to examine if responses differ. Findings from chi-square testing are discussed, looking for dependence between EEMagg and perceptions to motivator questions. Lastly, catalytic impacts are discussed, although statistical methods were not applied to survey responses because the survey did not collect homeowner perceptions or reasoning for adoption of additional EEMs. A summary of data collected from the survey is presented in Appendix B sections B.1 through B.5.

5.5.1 Energy savings and improved comfort were not drivers for adoption of EEMs

Research has postulated comfort and savings are key drivers to energy investments (Barr, Gilg et al. 2005, Bruel and Hoekstra 2005, Ingle, Moezzi et al. 2012, Murphy 2014); therefore, it is expected that in the scenario where a homeowner understands an EEM would improve comfort while reducing energy bills, the EEM would more likely be adopted. This scenario did not occur in this research. Homeowners did not invest in the recommended envelope (36.4% adopted) and HVAC (21.7%) improvements (both offering comfort and energy benefits) even though the results showed that the homeowners in the study understood the potential benefits. No statistical difference was observed (Table 10) between adopted and non-adopted EEMs for savings (p-value=0.100) and comfort (p-value=0.101). The two-sample test (Figure 20) indicates that adoption proportions for envelope and HVAC EEMs and proportions of homeowners' positive responses to savings or comfort motivators are statistically different (p-value<0.001 in each instance), indicating that these motivators were not a driving force in the adoption of these envelope and HVAC measures. While results indicate comfort and savings are not drivers to adoption for this sample of participants, there is potential for bias stemming from the small sample size of homeowners, building characteristics, or sampling bias.

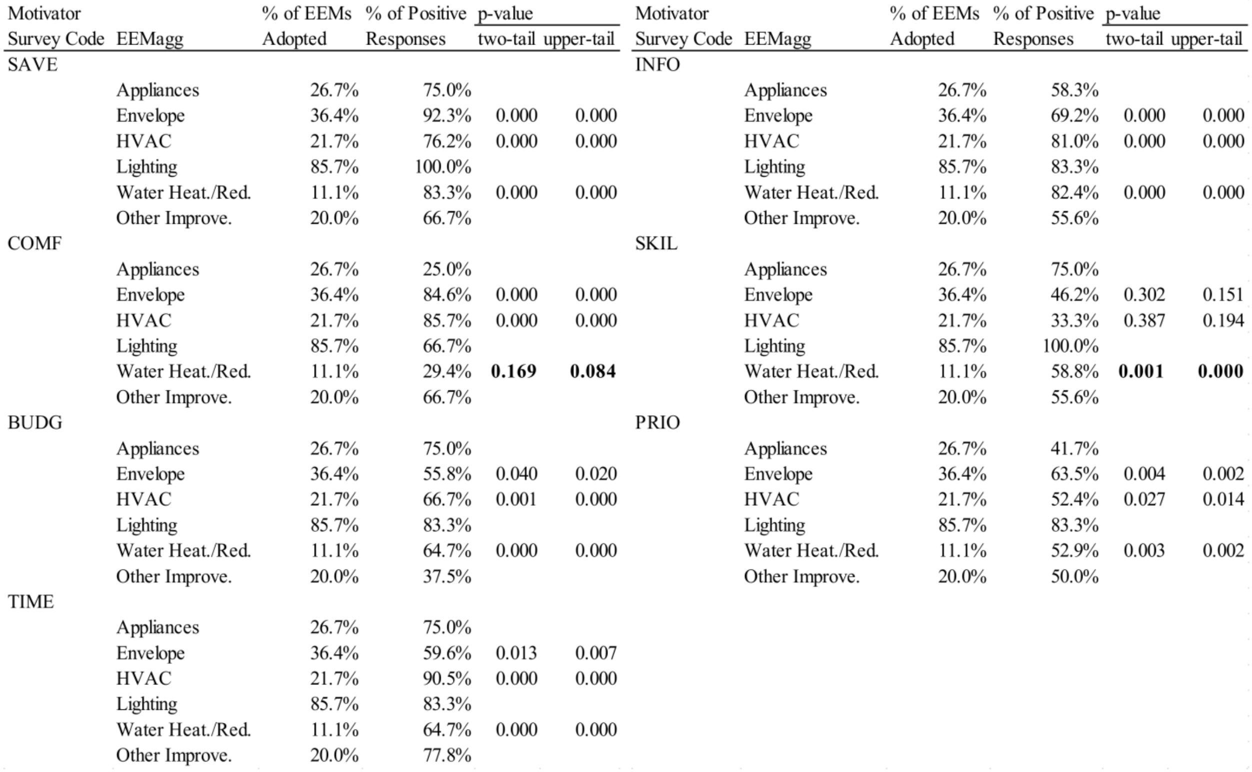
Table 10. Results for a two-tailed two-sample hypothesis test on the difference in proprotions at 95% confidence level, comparing homeowners' perceptions to motivator questions for EEMs they adopted and did not adopt, with testing performed on the total population of EEMs recommended (Total) and on the envelope EEMs recommended (Envelope).

Note: Portion is the percntage of responses that were positive (agree or strongly agree),
SAVE - This recommendation will save me money on my utility bills,
COMF - This recommendation will improve the comfort of my home,
BUDG - The cost of performing this recommendation is within budget,
TIME - I will have time to complete this recommendation,
INFO - I have the information needed to perform this recommendation,
SKIL - I have skills and/or abilities needed to perform this recommendation,
PRIO - This recommendation is a priority on my list of home improvement projects.

Sample Group	% of total sample	**SAVE**		**COMF**		**BUDG**		**TIME**		**INFO**		**SKIL**		**PRIO**	
		Portion	p-value	Portion	p-value	Portion	p-value	Portion	p-value	Portion	p-value	Portion	p-value	Portion	p-value
Total															
Adopter	30%	95%		81%		95%		95%		97%		73%		92%	
Non-adopter	70%	80%		63%		46%		59%		60%		43%		42%	
			0.044		**0.044**		**0.000**		**0.000**		**0.000**		**0.002**		**0.000**
Envelope															
Adopter	36%	100%		95%		95%		90%		95%		65%		95%	
Non-adopter	64%	88%		78%		31%		41%		53%		34%		44%	
			0.100		0.101		**0.000**		**0.000**		**0.001**		**0.031**		**0.000**

5.5.2 A lack of perceived skills acts as a barrier to adoption of envelope and HVAC measures

In response to the motivator question, “I have the skills and/or abilities needed to perform this recommendation,” homeowners showed a lack of confidence in *envelope* (53.8% negative response rate) and *HVAC* (66.6%) recommended improvements, summarized in Figure 20. This correlates with low adoption rates of envelope EEMs (36.4%) and HVAC EEMs (21.7%). These results are expected; HVAC and envelope improvements, such as adding attic insulation or insulating unconditioned basement air ducts, require more skill than installing low flow faucet aerators or upgrading to LED bulbs.



Motivator Survey Code	EEMagg	% of EEMs Adopted	% of Positive Responses	p-value two-tail	p-value upper-tail
SAVE					
	Appliances	26.7%	75.0%		
	Envelope	36.4%	92.3%	0.000	0.000
	HVAC	21.7%	76.2%	0.000	0.000
	Lighting	85.7%	100.0%		
	Water Heat./Red.	11.1%	83.3%	0.000	0.000
	Other Improve.	20.0%	66.7%		
COMF					
	Appliances	26.7%	25.0%		
	Envelope	36.4%	84.6%	0.000	0.000
	HVAC	21.7%	85.7%	0.000	0.000
	Lighting	85.7%	66.7%		
	Water Heat./Red.	11.1%	29.4%	**0.169**	**0.084**
	Other Improve.	20.0%	66.7%		
BUDG					
	Appliances	26.7%	75.0%		
	Envelope	36.4%	55.8%	0.040	0.020
	HVAC	21.7%	66.7%	0.001	0.000
	Lighting	85.7%	83.3%		
	Water Heat./Red.	11.1%	64.7%	0.000	0.000
	Other Improve.	20.0%	37.5%		
TIME					
	Appliances	26.7%	75.0%		
	Envelope	36.4%	59.6%	0.013	0.007
	HVAC	21.7%	90.5%	0.000	0.000
	Lighting	85.7%	83.3%		
	Water Heat./Red.	11.1%	64.7%	0.000	0.000
	Other Improve.	20.0%	77.8%		
INFO					
	Appliances	26.7%	58.3%		
	Envelope	36.4%	69.2%	0.000	0.000
	HVAC	21.7%	81.0%	0.000	0.000
	Lighting	85.7%	83.3%		
	Water Heat./Red.	11.1%	82.4%	0.000	0.000
	Other Improve.	20.0%	55.6%		
SKIL					
	Appliances	26.7%	75.0%		
	Envelope	36.4%	46.2%	0.302	0.151
	HVAC	21.7%	33.3%	0.387	0.194
	Lighting	85.7%	100.0%		
	Water Heat./Red.	11.1%	58.8%	**0.001**	**0.000**
	Other Improve.	20.0%	55.6%		
PRIO					
	Appliances	26.7%	41.7%		
	Envelope	36.4%	63.5%	0.004	0.002
	HVAC	21.7%	52.4%	0.027	0.014
	Lighting	85.7%	83.3%		
	Water Heat./Red.	11.1%	52.9%	0.003	0.002
	Other Improve.	20.0%	50.0%		

Figure 20. Summary of results for the upper-tailed two-sample hypothesis test on the difference in proportions.

Note, alpha equal to 0.05, in bold indicates failure to reject null hypothesis,
Water Heat./Red. is EEMagg Water Heating and Water Reduction
Other Improve. is EEMagg Other Improvements
SAVE - This recommendation will save me money on my utility bills,
COMF - This recommendation will improve the comfort of my home,
BUDG - The cost of performing this recommendation is within budget,
TIME - I will have time to complete this recommendation,
INFO - I have the information needed to perform this recommendation,
SKIL - I have skills and/or abilities needed to perform this recommendation,
PRIO - This recommendation is a priority on my list of home improvement projects.

In a study of energy efficiency adoption factors, Nair, Gustavsson et al. (2010) postulated low adoption of envelope improvements may stem from homeowners' lack of awareness, perception that envelope improvements are too cumbersome, or are not cost-effective. However, homeowners from this research believed they had the necessary *information* to adopt envelope improvements (upper-tail p-value < 0). Further, the recommendations fit within the homeowners' *budgets* (0.020), were within *time* constraints (0.007), and they agreed that the envelope improvements would lower utility *costs* (< 0). Counter to Nair et al, cumulative results suggest that skill acted more as a potential barrier than motivator to envelope (upper-tail p-value = 0.151) and HVAC (0.194) EEM adoption, over other motivators.

5.5.3 Envelope improvements are constrained by a homeowner's budget, time, information, and prioritization

A chi-square test for independence was performed to further evaluate relationships between motivator questions and adoption rates. At 95% confidence level, a p-value greater than the 0.05 rejects the null hypothesis of independence suggesting a relationship between a motivator and the adoption of the associated EEMagg grouping. Results are presented in Table 11. EEMagg *lighting* and *other improvements* did not have sufficient sample sizes for testing.

While the two-sample hypothesis tests provided evidence for the relationship between envelope and HVAC improvements with homeowners' perceived lack of skill to complete the EEM adoption, chi-square analysis reveals envelope EEMs are also dependent on a homeowner's budget, time availability, necessary information and home improvement project prioritization, the last of which includes HVAC improvements. The findings from the chi-square test were useful in determining the critical factors in stimulating homeowner investment in envelope EEMs; such that EEM recommendations should target homeowners' budgets, time, information and priorities in addition to reinforcing the skills necessary to realize an energy efficiency upgrade either through education and connection with trained professionals.

Table 11. Summary of contingency table results with bold values indicating dependency.

Note: $N_{\chi 2}$ is the sample size of EEM recommendations made within each of the four evaluated EEMagg groupings, df is degrees of freedom,
SAVE - This recommendation will save me money on my utility bills,
COMF - This recommendation will improve the comfort of my home,
BUDG - The cost of performing this recommendation is within budget,
TIME - I will have time to complete this recommendation,
INFO - I have the information needed to perform this recommendation,
SKIL - I have skills and/or abilities needed to perform this recommendation,
PRIO - This recommendation is a priority on my list of home improvement projects.

			Chi-Square p-value for each motivator (alpha = 0.05)						
EEMagg	$N_{\chi 2}$	df	SAVE	COMF	BUDG	TIME	INFO	SKIL	PRIO
Appliances	15	1	0.18	0.96	0.18	0.18	0.06	0.18	0.24
HVAC	23	1	0.10	0.22	0.42	0.34	0.15	1.03	**0.01**
Envelope	55	1	0.06	0.06	**0.00**	**0.00**	**0.00**	**0.02**	**0.00**
Water Heating and Water Reduction	18	1	0.47	0.26	0.19	0.19	0.45	0.14	0.10

5.5.4 As expected, water heating does not improve perceived comfort

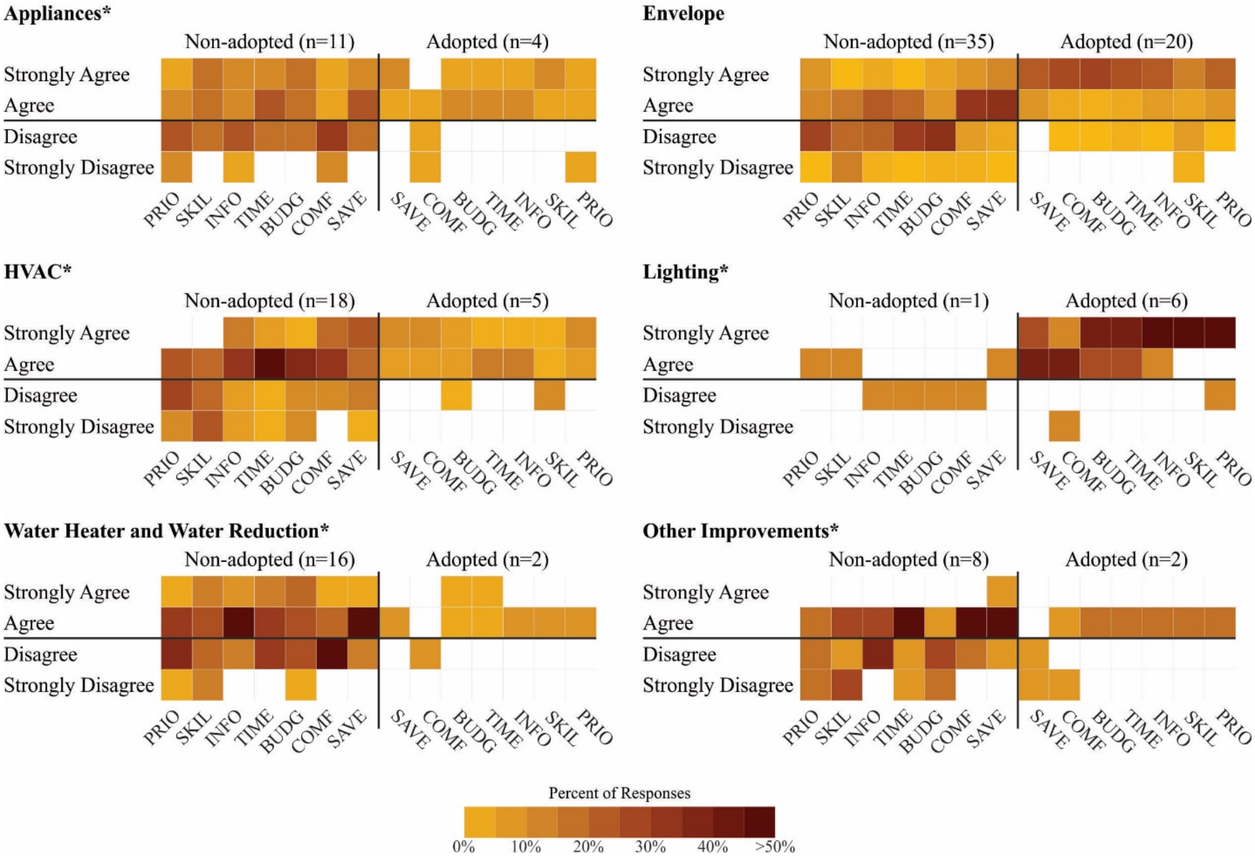
A low adoption rate (11%) for *water heating and water reduction* improvements and homeowners' negative perceptions (70.6% of responses) to the motivator question on *comfort*, resulted in a failure to reject the null hypothesis that the sample proportions were similar (upper-tail p-value = 0.084). While this result is not profound as water heating and use only factor into household comfort in minimal settings, most prominently the shower, it does provide insight into the relationship between *water heating and water reduction* EEMs and the motivation of comfort, in addition to demonstrating survey participants' deliberation in their responses.

Second, the 29.4% positive response rate to the question of comfort indicated that survey participants thought intently and offered meaningful opinions. It should be anticipated that *water heating and water reduction* and *appliances* were not positively viewed in terms of improving comfort. Conversely, homeowners' positive responses to comfort for *HVAC* and *envelope* were roughly 85%, demonstrating that homeowners read each question and responded honestly.

5.5.5 EEMs adopted were more positively perceived than those not adopted

The two-tailed hypothesis test was done for the cumulative 128 EEMs recommended to homeowners, and separately for EEMagg group *envelope,* which provided a large enough sample for both adopted (20) and non-adopted (35). The other EEMagg groups did not have sufficient sample sizes for statistical analysis, although Figure 21 provides a heat map for visual assessment.

Results for the cumulative 128 EEM sample (Table 10) reveal a statistically significant difference for each of the seven motivator questions between the EEMs adopted and not adopted (p-value<0.05). Moreover, results for the EEMagg *envelope* show a statistical difference between motivator questions pertaining to budget, time, info, skill, and priority. Figure 21 partially supports these findings with qualitative evidence illustrating a seemingly divergence of perceptions for the other EEMagg groups between adopted and non-adopted EEMs, i.e. adopted EEMs show fewer negative responses than non-adopted EEMs. Together, the results produce statistical evidence in support of the hypothesis that adopted EEMs were perceived more positively over non-adopted EEMs.


Appliances*

Envelope

HVAC*

Lighting*

Water Heater and Water Reduction*

Other Improvements*

Figure 21. A heat map illustrating homeowners' responses to motivator questions organized by EEMagg and responses for EEMs adopted and not adopted. Note: * indicates a sample size too small for statistical analysis, "n" denotes the sample size for the EEMagg adopter and non-adopter groups.

5.5.6 Catalytic impacts may be the unintended benefit of home energy assessments; 101 additional EEMs implemented outside those recommended signals

The NELC program intends to educate homeowners through informative energy assessments and personalized reports, spurring additional investments in energy efficiency measures outside of those improvements recommended to homeowners. This catalytic impact is commonly not measured in research evaluating the efficacy of energy conservation programs. This research aimed to quantify those secondary investments through the second section of the survey asking homeowners explicitly what other investments were made outside of those recommended through the NELC energy assessment report.

Homeowners implemented an *additional* 101 energy improvements since receiving their energy assessment. That is an increase of 159% over the 39 adopted from the NELC energy assessment reports. Implementation of additional EEMs ranged from zero in three households to nine in one household, with a mean of 3.7 EEMs and a mode of 4 EEMs. Distribution of investments is (details in Figure 22): envelope (31), other improvements (18), lighting (16), water heating and water reduction (14), HVAC (12) and appliances (10).

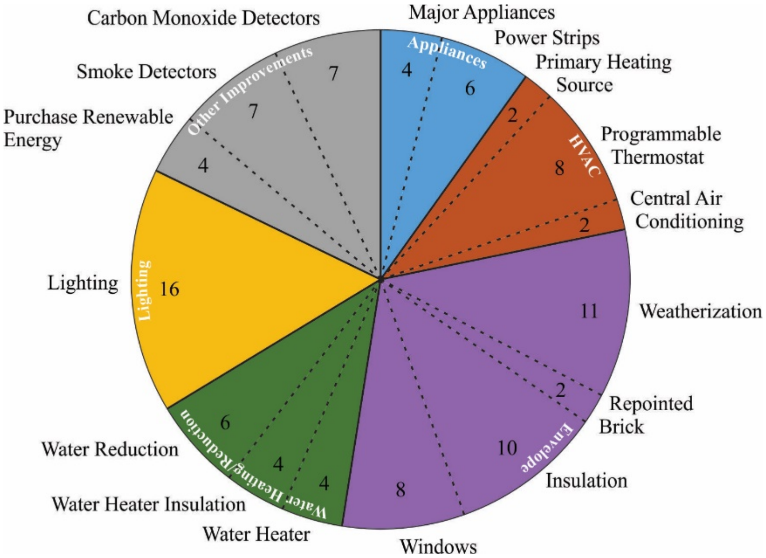


Figure 22. Detailed distribution of homeowner-identified and implemented (catalytic) energy efficiency investments, organized by EEMagg and EEMsub groups. Note: Water heating and water reduction is abbreviated to water heating/reduction.

The intent of the survey was to evaluate homeowners' motivations for their decision on whether or not to adopt a recommended energy efficiency measure, intended to gauge the efficacy of the NELC program; however, failing to explore homeowners' motivations for the additional EEMs implemented outside of those recommended. While I labelled the additional EEMs implemented as a catalytic impact of the NELC program, it cannot be directly determined that homeowners chose to invest in the additional EEMs directly because of the NELC program.

However, it could be noted that the additional 31 envelope improvements from 67% of responding homeowners might indicate the possibility of a more direct catalytic effect. As previously discussed, envelope improvements are harder for homeowners to realize stemming from lack of awareness and proper information; although, of the 31 additional investments 10 were upgrades to insulation and 8 were upgrades to windows, including single pane to double pane or installation of storm windows, which are more comprehensive upgrades than installing weatherization measures.

5.6 CONCLUSIONS ON THE EFFICACY OF THE NELC PROGRAM

A survey of homeowners participating in the NELC holistic energy assessment program between 2012 and 2014 was designed and implemented. The survey measured adoption rates of recommended EEMs and homeowners' motivations for their decision on adoption. Further, the survey aimed to elucidate the implementation of self-identified EEMs outside of those recommended by the NELC assessment report. A response rate of 33% was recorded including representation from each of the three years of assessments. Efficacy was measured through reported adoption rates (30% of EEMs recommended or 85% of households adopting one EEM) and implementation of self-identified measures (101 additional EEMs in 89% of households). From the findings of this research, two recommendations are presented: (1) policy to standardize publicly available energy conservation program reporting and (2) re-exploration of motivators and barriers to energy efficiency investment.

In assessing the efficacy of the NELC program, comparative evaluation with other existing programs was difficult because of the array of metrics employed and reported by energy conservation programs, including but not limited to program costs, measured energy reductions in homes, and adoption rates of EEMs (Fuller, Kunkel et al. 2010). Because energy reduction verification is difficult, programs may opt for verifying adoption rates through surveys. A review of literature reveals a range of reported adoption rates, between 30 and 85%; even though adoption calculations may be “per EEM” or “per household” significantly impacting the final percentage (Fuller, Kunkel et al. 2010, Ingle, Moezzi et al. 2012, Palmer, Walls et al. 2013, Murphy 2014). *EEM* adoption rates are calculated from those EEMs adopted versus total recommended, while *household* adoption rates are calculated from the number of households adopting at least one EEM. Adoption rate denominators are not always clearly stated and may hinder comparative evaluation between programs. In this research the NELC program demonstrated 30% adoption per EEM and 85% adoption per household measuring the direct efficacy of the program at both ends of the spectrum of reported adoption rates.

Public policy aimed at standardizing evaluative metrics for assessing program efficacy and creating a repository of reported program outcomes would generate comparable data applicable by energy conservation programs in assessing performance across multiple energy conservation programs. Further, a publicly available database, even at a regional scale, would be invaluable to the research community in understanding the roles of program design, e.g. information delivery method, incentives offered or energy efficiency measures offered, and customer orientation, e.g. geospatial or socioeconomic, play in homeowner investment of energy efficiency measures.

The survey implemented in this research was developed around the existing body of literature on motivators and barriers to energy efficiency in residential buildings. Results of the two-sample hypothesis test reveal that homeowners had positive perceptions for many of the motivators with respect to the recommended EEM, but adoption rates for the EEMagg groups remained relatively low with an overall average of 30%. Moreover, the addition of catalytic implementation of EEMs showed a 159% increase in total EEMs invested, which included comprehensive upgrades such as double pane windows, primary heating equipment and attic insulation. This suggests two key findings: (1) homeowners were motivated to invest in comprehensive retrofits and (2) the traditional list of motivators used in authoring homeowners' energy assessment reports and designing the survey was not inclusive of all homeowners' motivations. Simply put, I have concluded that implementation of an EEM is more nuanced, and the decision and actions are a part of a complex decision process that should be explored in future energy policy programs and studies.

While a portion of homeowners invested in NELC recommended comprehensive upgrades, more homeowners invested in self-identified improvements. It is recommended that the building energy efficiency research community should consider expanding the commonly accepted motivators and barriers, as this research suggests cost savings and comfort were not prevalent drivers as postulated in other research (Barr, Gilg et al. 2005, Bruel and Hoekstra 2005, Ingle, Moezzi et al. 2012, Murphy 2014). Gaps in current literature exploring superficial benefits of energy improvements (e.g. aesthetics or community perceptions) have not been extensively considered, and are difficult to quantify requiring the continued integration of behavioral and building sciences in multidisciplinary project teams.

If it is considered that the adoption rates reported in other studies were collected from professionally performed energy audits while those reported in this research project are from student authored reports, the comparable 30% EEM adoption rate supports the concept of using community interconnectivity to engage homeowners through student performed energy assessments.

6.0 SYNERGIZING DISPARATE COMPONENT-LEVEL ENERGY RESOURCES INTO A SINGLE WHOLE BUILDING TOOL TO SUPPORT ENERGY CONSERVATION ACTION IN SMALL COMMERCIAL BUILDINGS

This chapter addresses research question 3, *can a robust and technically sound program, modeled after the residential, be developed to reduce energy consumption in small commercial buildings?* The research presented is a reproduction of an article that has been submitted to the journal Building and Environment.

Ketchman, K. J., Khanna, V., Parrish, K., and Bilec, M. M., (2017 submitted). "Synergizing Disparate Component-Level Energy Resources into a Single Whole Building Tool to Support Energy Conservation Action in Small Commercial Buildings." submitted to Building and Environment

6.1 INTRODUCTION

Efforts to combat global dilemmas posed by anthropogenic environmental degradation have partially taken shape around building energy efficiency. While advances in building energy use have been made for large commercial buildings, efforts in energy efficiency for small commercial buildings (SCBs) have been lacking. Yet in the U.S., SCBs (under 4,645 m^2 – 50,000 ft^2 – in floor area) represent 94% of commercial buildings by number and approximately 9% of national primary energy consumption (U.S. EIA (2012). Globally, the International Energy Agency illustrated the global significance of the enterprises occupying SCBs; an estimated 99% of enterprises are small or medium-sized enterprises (SMEs), accounting for approximately 13% of global annual primary energy consumption (IEA 2015).

Support for SCBs has slowly risen from governments, non-profit organizations, and research. The passage of the Energy Efficiency Improvement Act of 2015 (S. 535 - 114th Congress 2015) tasked the U.S. EPA with developing a *Tenant Star* program similar to their *EnergyStar* program, which launched in 1992 and has since seen steady growth of sales of EnergyStar certified appliances (U.S. EPA 2012). An objective of the *Tenant Star* program is to address energy efficiency of individual spaces within buildings, engaging both enterprises and building owners. The Berkeley Lab, in partnership with Architecture 2030, develop a small commercial whole-building toolkit, aiming to provide energy profiles and energy efficiency improvements to participating partners (Architecture 2030 2016). Additionally, research performed by Barnes and Parrish (2016) developed a library of building case studies intended to provide guidance to energy conservation programs on specific key barriers to adoption, widely observed throughout the SCB sector.

While these aforementioned efforts are increasing awareness and providing technical support, additional efforts are needed to advance energy efficiency in this critical building sector. The SCB sector is complex and heterogeneous as it has disparate building and organizational characteristics, along with varying commercial activities. The U.S. Energy Information Administration (EIA) defines sixteen commercial activities occurring in buildings, from food service to office and mercantile with each activity presenting a host of barriers to energy efficient technologies and practices. Commonly experienced barriers in SCBs are a lack of access to information and limited access to capital (NSBA 2011, U.S. DOE 2013, Barnes and Parrish 2016). In part, this research attempted to directly address the informational barrier and indirectly addresses SCBs' limited access to capital through development of a publicly available resource so SCBs can effectively focus their investments.

In prior work, I observed that many different calculators and methods existed for building energy efficiency efforts (Ketchman, Riley et al. 2016). For example, EnergyStar and the U.S. Department of Energy (DOE) have made public a portfolio of energy efficiency calculators for residential and commercial appliances (U.S. DOE 2014, Energy Star 2016), while national laboratories offer another key source of energy information, ranging from providing benchmarks for standby energy (Berkeley Lab 2014, WBDG and NIBS 2014) to highly specialized energy calculators (PNNL 2016). However, I argue that one overarching resource is needed to serve the small building sector that is usable and accurate, while considering the unique needs of SCBs. To address these needs, I developed the *Building Energy Assessment Resource* (BEAR). The aim was to synthesize existing disparate energy quantification methods and resources from the U.S. EPA and the U.S. DOE into one resource (U.S. DOE 2014, Energy Star 2016), with the ultimate goal of reducing energy consumption in the small commercial building sector.

Drawing upon existing research, BEAR is intended as an informative energy resource, accessible to small building owners and tenants and operational with minimal parameter inputs (Riley, Whelton et al. 2012, Ketchman, Riley et al. 2016). The design objectives of BEAR include *accuracy* (i.e. the difference between BEAR energy estimates and energy bills), *robustness* (i.e. the ability to be used in the portfolio of building activities), *scalability* (i.e. the ability to accurately estimate energy at varying building sizes and complexity), and *practicality* (i.e. can be used by building stakeholders). This chapter will evaluate if BEAR achieves the first three design objectives through implementation in thirteen SCBs.

A review of measurement-based energy quantification methods provides context to the bottom-up disaggregation approach used to create BEAR. The remainder of the chapter is organized as follows. Section 6.3 presents the development of methods underpinning the six steps for using BEAR. Section 6.4 summarizes the thirteen buildings a part of the case study. Section 6.5 presents results and discussion of the precision and accuracy of BEAR in estimating tenants' annual energy consumption in relation to collected energy bills. Lastly, findings and future advancements of BEAR are discussed.

6.2 BACKGROUND OF ENERGY QUANTIFICATION AND DISAGGREGATION METHODS

One approach to stimulate energy efficiency investments is to provide informative energy evaluation resources to building stakeholders. For the purpose of this chapter an *energy evaluation resource* is a resource that enables the assessment of energy use in a building or space by providing detailed energy use information, including simulated energy profiles, disaggregated end-use energy data, or comparable metrics. Energy evaluation resources have many parts, but arguably the most important is the energy quantification method, which is a driving force of performance in an energy evaluation resource. Energy quantification methods – the method used within an energy evaluation resource to quantify energy use at varying levels (e.g. building, tenant, or appliance) – may be categorized into three types: calculation-based, measurement-based, and a hybrid of the two (Wang, Yan et al. 2012). Each method has its drawbacks, such as high upfront costs for software or implementation associated with calculation-based methods. Employing a *fit-for-purpose* approach, where the ideal design is the least complex while meeting outcome goals, this research identified measurement-based energy quantification methods as the best fit. The following review presents the current state of measurement-based energy quantification methods, specifically *top-down* and *bottom-up* energy bill disaggregation, and a brief review of two commercial-specific whole-building energy disaggregation resources currently available.

6.2.1 Energy bill disaggregation methods

Energy bill disaggregation is the process of dissecting whole building energy consumption into major end-uses through use of *disaggregation algorithms* or *disaggregation estimations* (Wang, Yan et al. 2012). Disaggregation algorithms apply understanding of relationships between an energy system and the underlying determinants for energy consumption (e.g., space heating and heating degree days); while disaggregation estimations apply knowledge of energy consumption for individual systems (e.g. rated power and hourly use of a computer monitor). *Bottom-up* energy bill disaggregation employs both disaggregation algorithms and estimations.

A bottom-up approach compiles power demand and operational hours of appliances to determine energy consumption using estimation algorithms, prior to reconciling with energy bills (Field, Soper et al. 1997, Webber, Roberson et al. 2006, Menezes, Cripps et al. 2014, Gandhi and Brager 2016). Lee, Yik et al. (2003) defined an estimation algorithm for quantifying appliance electricity consumption, based on equipment numbers, rated power demand, and hours in operation. Using their estimation algorithm, it is also possible to estimate electricity consumption for plug-load and lighting end-uses, before reconciliation with energy bill data to obtain cooling energy consumption.

Bottom-up energy disaggregation approaches provide high granularity of energy consumption, enabling the provision of targeted recommendations for improving energy efficiency. Moreover, collected appliance-level data organized into a publicly available database is considered a highly useful resource to consumers, research, and policy makers (Heidell, Mazzucchi et al. 1985, Armel, Gupta et al. 2013).

The bottom-up approach does have disadvantages predominantly in the form of time requirements to catalogue appliances. Practitioners of bottom-up methods collect an inventory of appliances and equipment in a building, which can take several hours for a building under 465 m^2. As one moves up the SCB size range towards a 4,645 m^2 building, the time investment grows (Lanzisera, Dawson-Haggerty et al. 2013). However, development of an appliance-level database especially at a national level would help to reduce these commitments.

6.2.2 Existing whole building energy disaggregation resources

Approaches taken to provide the SCB sector with detailed energy information include the Building Energy Asset Score and Small Commercial Toolkit (Regnier 2014, U.S. DOE 2017).

The U.S. DOE and Pacific Northwest National Laboratory (PNNL) released the Building Energy Asset Score with a user-interface and EnergyPlus modeling software for whole building energy analysis (Crawley, Lawrie et al. 2001, U.S. DOE 2017). This program ranks a building's energy efficiency based on user-input energy assets (e.g. HVAC, lighting, water heating, and design characteristics), comparing with other similar buildings. The tool enables users to model their building by inputting operational and physical constraints, while outputting building performance metrics and recommendations for energy improvements. However, the tool has shortcomings in addressing the complete portfolio of building activities in SCBs. The Building Energy Asset Scoring Tool accounts for office, retail and other similar building use types, but omits food service and food sales, which are the two most energy intensive building uses in small commercial buildings (U.S. EIA 2012).

Another resource developed by the Berkley Lab in partnership with the Architecture 2030 Challenge (Architecture 2030 2016) is the Small Commercial Toolkit package. This resource includes a set of technical tools and programs for analyzing energy consumption (Regnier 2014). Only recently has the Small Commercial Toolkit been made publicly available (cbes.lbl.gov/buildings), preventing an in-depth review of the tool.

In reviewing the literature, I propose the development and implementation of a bottom-up energy bill disaggregation resource that fits the needs of SCB stakeholders. Further, examination of existing energy disaggregation resources revealed limitations in quantifying commercial cooking (Burman, Hong et al. 2014, Lee, Hong et al. 2015). BEAR aims to address limited access to information in the food service sector.

6.3 METHODS

In developing the building energy assessment resource, I drew from key research on fit-for-purpose design (i.e. least level of complexity to meet a desired outcome) (Gaetani, Hoes et al. 2016) in coordination with three guiding criteria as proposed by van Dijk, Spiekman et al. (2005): transparency, reproducibility, and robustness. The design objectives include accuracy, robustness, scalability, and practicality. This section will review the steps in application of BEAR, in addition to the methods used. The six steps are illustrated in Figure 23, starting with the determination on appropriateness through energy efficiency measure savings computations.

6.3.1 BEAR Appropriateness (Step 1)

I adapted Gaetani, Hoes et al. (2016) fit-for-purpose method for selecting the appropriate building energy simulation package in the design of BEAR resulting in step 1, the determination if BEAR is appropriate. Four questions are posed, which BEAR aims to address: (1) who will use BEAR, (2) what are the user's motivations, (3) what are the user's barriers, and (4) when will BEAR be used, illustrated in Figure 23. BEAR was specifically designed for SCB owners and tenants experiencing barriers associated with a lack of access to information or capital (Fleiter, Schleich et al. 2012, Trianni and Cagno 2012, Kostka, Moslener et al. 2013, Timilsina, Hochman et al. 2016, Fresner, Morea et al. 2017); although, other barriers exist (Olsthoorn, Schleich et al. 2017). In terms of SCB stakeholder motivations' for investing in energy efficiency improvements four common themes can be assembled from previous research, which BEAR may assist: (1) lower operational costs, (2) reduce energy consumption, (3) target specific equipment for upgrade, and (4) improve public image through sustainability (Kontokosta 2016, Kuppig, Cook et al. 2016, Wang, Li et al. 2016). Lastly, BEAR was designed for use in existing buildings during occupancy. If a SCB stakeholder determines BEAR to be applicable, the next step is to perform an energy audit.

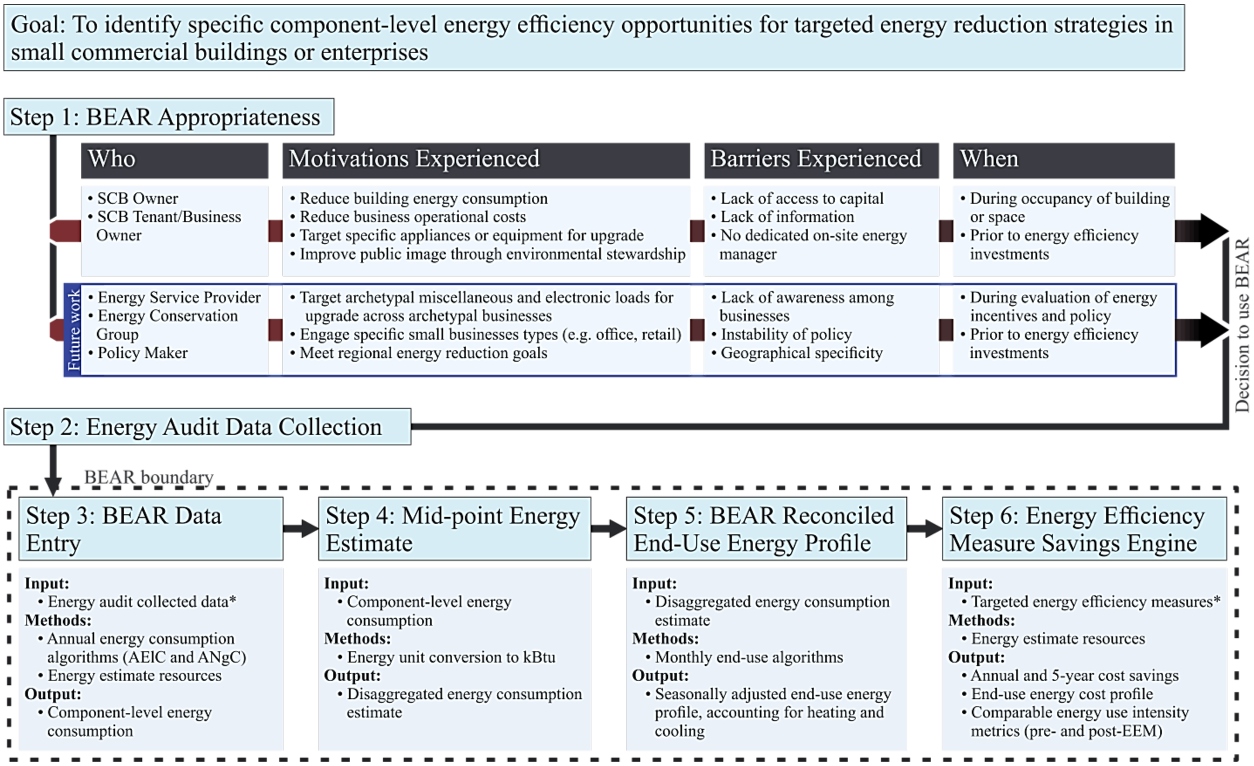


Figure 23. Illustration of the six steps for implementing the Building Energy Assessment Resource (BEAR). Note: within the BEAR boundary an asterisk (*) designates an input that is manually entered by the user. All other inputs and outputs are automated. Future work is outlined in blue in Step 1 and includes the expansion of BEAR into upstream energy service communities and policy makers (Ketchman, Khanna et al. 2017 submitted).

6.3.2 Energy Audit Data Collection (Step 2)

The BEAR data collection falls within a holistic version of an ASHRAE Level II energy audit, combining energy bill analysis, detailed cataloging of appliances, and collection of employee operational information (i.e. hours using appliances) (ASHRAE 2011, Riley, Whelton et al. 2012, Ketchman, Riley et al. 2016). Table 12 provides a summary list of data collection needs.

Table 12. Summary list of energy components, considered part of the system inventory, and the component-level information necessary for BEAR data input.

		Modal Power Rating (W)			Daily Modal Operation (hr), weekday and weekend			Fuel Capacity (Btu/hr)	Annual Energy Rating	
Component	Count	Active	Low	Off	Active	Low	Off		kWh/yr	Btu/yr
Office appliances	x	x	x	x	x	x	x			
Misc. electric loads	x	x	x	x	x	x	x			
Lighting fixtures	x	x	x	x	x	x	x			
Cooking appliances	x	x	x	x	x	x	x			
Cooking equipment	x				x			x		
Refrigerators	x								x	
Freezers	x								x	
Hot water heaters	x								x	x
Primary heating	x							x		
Primary cooling	x							x		
Ventilation equipment	x								x	

The *bottom-up* method used in BEAR requires component-level information for the energy bill analysis, including the number of appliances or equipment of the same model, modal power rating, modal operational hours for weekdays and weekends, and fuel capacity, typically for primary heating and cooking units. If the modal power data or operational hours are not discrete, such as in refrigeration, hot water heating, or primary heating and cooling equipment where operation is commonly unmonitored, data collection may rely on annual energy ratings, e.g., those provided by an EnergyGuide label (FTC 2016), in addition to a model number to obtain operational information through a manufacturer’s specification sheet.

Outside of energy consumption data collection, general building information is collected (e.g. floor area, number of floors, and a window type), and business operational information (e.g.

operating hours, number of employees, and heating and cooling set points). This information is used in calculating energy costs and savings potential, in addition to comparable energy use intensity metrics. The handling of data is discussed in the next steps which reviews the BEAR interior computations and resource integration.

6.3.3 Bear Data Entry (Step 3)

The BEAR suite was developed from existing energy disaggregation research and incorporates both disaggregation algorithms and disaggregation estimations to quantify energy consumption (Lee, Yik et al. 2003, Wilkins and Hosni 2011, U.S. DOE 2014, Energy Star 2016, Energy Star 2016, CEC 2017). Development of annual energy consumption algorithms and the assemblage of energy estimate resources (i.e. calculators, benchmarks, or databases that provide an estimate of energy use) are presented. Images of BEAR corresponding with the steps for using BEAR are provided in Appendix C.

6.3.3.1 Annual energy consumption algorithms

The developed energy disaggregation algorithms were derived in part from the previous research employing energy balance equations (Yan, Wang et al. 2012) and appliance and equipment operational modes to improve accuracy of energy consumption estimates (Menezes, Cripps et al. 2014). In particular, the annual electricity consumption Equation (1) developed by Lee, Yik et al. (2003) was reformulated to introduce operational mode parameters.

$$\mathbf{AEC}_{\boldsymbol{Equip,i}} = \left(\sum\nolimits_{\boldsymbol{j}} \mathbf{N}_{\boldsymbol{i,j}} \times \mathbf{W}_{\boldsymbol{i,j}}\right) \times \boldsymbol{UF}_{\boldsymbol{i}} \times \mathbf{AOHr} \qquad \textbf{Equation 1}$$

In Equation (1), $N_{i,\,j}$ represents the number of *i*th type of equipment with similar *j*th parameters (e.g. capacity); $W_{i,\,j}$ is the power demand (watt); UF_i is a utilization factor equal to the fraction of the annual operating hours (*AOHr*) of the building when the equipment is operating.

I determined that the utilization factor, *UF*, and the annual operating hours could be replaced by the equipment annual usage hours ($AUHr_{i,\,p}$); the annual operating hours of the *i*th type of equipment for the *p*th power mode. Replacing the power term ($W_{i,j}$) with the fuel term ($BTU_{i,j}$) enables calculation of energy use in commercial kitchen equipment. The amended annual energy consumption equations for the *i*th equipment type with similar *j*th parameters for the *p*th operating mode becomes equations (2) for electricity and equation (3) for natural gas:

$$\mathbf{AElC}_{\boldsymbol{Equip},\boldsymbol{i},\boldsymbol{j}} = \left(\sum\nolimits_{\boldsymbol{j}} \mathbf{N}_{\boldsymbol{i},\boldsymbol{j}} \times \mathbf{W}_{\boldsymbol{i},\boldsymbol{j},\boldsymbol{p}}\right) \times \mathbf{AUHr}_{\boldsymbol{i},\boldsymbol{p}} \qquad \textbf{Equation 2}$$

$$\mathbf{ANgC}_{\boldsymbol{Equip},\boldsymbol{i},\boldsymbol{p}} = \left(\sum\nolimits_{\boldsymbol{j}} \mathbf{N}_{\boldsymbol{i},\boldsymbol{j}} \times \mathbf{BTU}_{\boldsymbol{i},\boldsymbol{j},\boldsymbol{p}}\right) \times \mathbf{AUHr}_{\boldsymbol{i},\boldsymbol{p}} \qquad \textbf{Equation 3}$$

In the electricity equation, operating modes are relegated to three power levels: active, low, and off (Wilkins and Hosni 2011). Appliances exhibit a range of power demand when active, including potentially a mid-active power demand. Modal-specific power level information is scarcely available to the public sector. Energy Star certified appliances are listed with detailed power data, including modal data for certain appliances, e.g. computers (Energy Star 2016). During the data collection step, some assumptions may need to be made regarding modal power.

Modal power data for the natural gas equation can be difficult to derive, in most cases burners, stoves, and griddles regulate natural gas consumption through manually controlled valves. Therefore, it is useful to identify a range on the dial associated with a low mode and active mode. For example, on a scale of one to ten, anything at or below five not including zero may be considered low, while above five is active. While assumptions must be made, the benefits of quantifying commercial kitchen natural gas consumption outweigh the uncertainty of assumptions, because the food service sector consumes 370% more natural gas per square foot than the average of all other commercial enterprises (U.S. EIA 2012). In particular, BEAR is a first step in providing the food service sector with a whole building energy assessment resource capable of disaggregating energy use in commercial kitchens.

The annual energy consumption algorithms provide energy consumption totals for the following end-use consumers: appliances, lighting, and cooking appliances and equipment. Hot water heating, ventilation, refrigeration, and primary heating and cooling equipment rely on energy estimate resources, as outlined in the next section.

6.3.3.2 Energy estimate resource identification

Energy estimate resources include calculators, databases, and benchmarks, and utilize data collected through an energy audit (step 2) to estimate daily energy consumption or appliance modal parameters. Qualifying resources integrated to BEAR were required to meet three guiding criteria: transparency, reproducibility, and robustness (van Dijk, Spiekman et al. 2005).

Calculator-based resources were sourced through the Energy Star (Energy Star 2016) and Office of Energy Efficiency and Renewable Energy (U.S. DOE 2014), where calculators are available for many common appliances and equipment. Each computational resource, and supporting documentation, was entered to the BEAR suite of resources as a separate entity and labeled appropriately.

Database and benchmark resources identified, include the Energy Star certified product database (Energy Star 2016), California Energy Commission appliance database (CEC 2017), and the Berkeley Lab (2014) data table of measured standby power consumption of common office appliances. Databases may be updated frequently as appliances achieve certification, e.g. Energy Star. Therefore, URL information is incorporated to the BEAR suite directing users to the appropriate resource. A complete list of energy estimate resources is provided in Appendix section C.1.

The energy estimate resources provide energy consumption totals for the following end-uses: hot water heating, ventilation, refrigeration, and heating and cooling equipment. These five end-uses are difficult to quantify through algorithms, as operation is typically unmonitored and may be seasonal. Additionally, energy estimate resources may be useful in filling missing modal or fuel capacity data when information is unavailable at the audit.

Entry of data to the BEAR inventory (see Appendix C.2) outputs annual energy consumption for the appliances and equipment in a building or space. Appliances and equipment are manually sorted by the user into one of eight end-uses, which are used to then derive a mid-point energy estimate.

6.3.4 Mid-point Energy Estimate (Step 4)

The mid-point energy estimate aggregates the component-level energy consumption calculated in the system inventory (labeled *input* in Figure 23) into eight end-uses (*output*) as assigned by the user, prior to reconciliation with a tenant’s energy bills. The mid-point estimate serves three purposes. First, the mid-point estimate converts electric and natural gas consumption into equivalent kBtu units for the next step in the BEAR quantification process. Second, the estimates are vital to the generation of targeted energy efficiency measures intended to reduce energy consumption for specific appliances or equipment. Lastly, the mid-point estimate provides annual energy consumption totals for the non-seasonal end-uses.

For the purpose of this study, the mid-point estimate also serves as a means to evaluate the accuracy of BEAR in relation to tenants' energy bills. Appendix section C.3 provides a screenshot of BEARs mid-point estimation page.

6.3.5 BEAR Reconciled End-Use Energy Profile (Step 5)

The mid-point end-use energy estimates are reconciled with energy bills to determine seasonally adjusted heating and cooling loads, deriving the final end-use energy profile for a building or commercial space. The process of reconciling estimated energy consumption with energy bills involves quantification, dependent on fuel source, of two monthly energy loads: (1) non-seasonal and (2) seasonal. Reconciled energy bills are illustrated in Appendix C sections C.4 and C.5.

Non-seasonal energy loads include, appliance, cooking, lighting, refrigeration, water heating, and ventilation. These are considered independent of seasonal variation and are evenly distributed across the twelve months of energy bills, similar to other studies (Field, Soper et al. 1997, Yan, Wang et al. 2012).

Seasonal loads include heating and cooling end-uses. There are two scenarios when reconciling seasonal loads: (1) a building operates on a fuel-mix (e.g. electricity and natural gas) and (2) a building operates on electricity only. In a fuel-mix building, after removal of non-seasonal loads the remaining energy is assigned to the appropriate seasonal end-use. In cases where water heating or cooking end-uses operate on both electricity and natural gas, BEAR apportions accordingly when reconciling with energy bills. In electricity-only buildings seasonal end-use apportionment must be determined using a monthly adjustment factor equal to the monthly ratio of heating degree days (HDD) to cooling degree days (CDD). The resultant is the apportionment of monthly electricity use to heating and cooling end-uses.

With the reconciled end-use energy profile and detailed component-level energy estimates, users engage the energy efficiency measure savings engine, identifying targeted energy reductions at the building- and appliance-levels.

6.3.6 Energy Efficiency Measure Savings Engine (Step 6)

The final step in BEAR is the quantification of energy reductions from the energy efficiency measure (EEM) savings engine, which in BEAR's first generation utilizes a user-driven exploration of EEMs (Appendix C section C.6).

Using the information gained through the BEAR steps, in coordination with the integrated energy estimate resources, users are able to assess targeted energy reductions. To help guide decisions, building performance metrics are calculated for the reconciled energy profile (step 5) and the amended energy profile after EEM improvements are entered (step 6). This provides users with analogous data of current and potential energy profiles, providing data antecedent to investing in energy improvements.

BEAR integrates fit-for-purpose design in development of a bottom-up energy disaggregation method intended to overcome financial and informational barriers experienced by small commercial stakeholders. To fully explore the design objectives and limitations of BEAR, a case study of thirteen buildings was performed.

6.4 MULTI-BUILDING CASE STUDY

BEAR's design was intended to function effectively across small commercial building activities To build a portfolio of building activities, collaboration with the Pittsburgh 2030 District, convened by the Green Building Alliance, was formed (2030 Districts 2012, GBA 2017). The Pittsburgh 2030 District program is a network of building owners aimed at reducing energy and water consumption, transportation emissions and improving indoor air quality. At the end of 2016, nearly 70% of downtown Pittsburgh and the Oakland neighborhood, where the University of Pittsburgh is located, had partnered with the Pittsburgh 2030 District affording this study access to building owners and tenants in retail, office, and food service industries. As part of partnership, buildings are mandated to provide monthly energy bills to the Pittsburgh 2030 District, updating annually, which were used in evaluating BEAR.

6.5 RESULTS AND DISCUSSION

BEAR was implemented in thirteen small commercial buildings, constituting 8,738 m^2 of floor area and an annual total of 12.6 billion Btu of energy consumption. Within the thirteen buildings, 21 sub-metered and 28 master-metered small commercial enterprises operated. A summary of building data is presented in Table 13.

It should be noted that building tenant J.2, included in Table 13 for reference, is considered an outlier in this research, because of services provided. Tenant J.2 is a health studio and hair salon offering wellness and salon services, including tanning and laser skin care services, which operate high-energy appliances irregularly and contained major thermal envelop deficiencies. The intent of this study is to test BEAR under more generalized building conditions, leading to the removal of tenant J.2 from results.

Table 13. Summary of buildings and tenant information. Nested enterprises are those tenants lacking sub-metered energy data, but were a part of the BEAR case study building. If no nested enterprises are listed, then all tenants are accounted for in tenant code column.

Tenant Code	Primary Building Use	Weekly Op. Hours	Floor Area (m^2)	# of Workers	HDD	CDD	Electric Bill (MMBtu)	Nat Gas Bill (MMBtu)	Nested Enterprises
A.1	Retail	56	111	9	5561	126	264	0	
A.2	Retail	56	29	2	5561	126	41	0	
A.3	Retail	65	37	1	5561	126	36	0	
B	Office	50	483	11	5707	423	121	78	(1) office
C.1	Office	50	353	13	6404	485	76	122	
C.2	Office	50	177	6	6404	485	37	108	
D	Office	45	491	25	6404	418	301	143	(6) office tenants
E.1	Food Service	55	225	15	6960	734	730	397	
E.2	Office	60	307	25	6960	734	92	207	
F	Food Service	105	590	8	7630	734	356	689	(1) food service
G	Food Service	80	83	3	557	213	231	35	(1) food service
H.1	Food Service	126	167	10	7335	734	594	1144	
H.2	Office	40	92	3	6960	568	47	121	
H.3	Office	55	358	30	7630	734	126	208	
H.4	Food Service	73	94	5	6960	568	189	502	
I	Retail	60	334	5	5666	568	160	135	(1) retail tenant
J.1	Food Service	106	488	9	7630	734	417	1077	
J.2	Retail	70	163	3	6763	568	437	56	
K	Office	50	232	13	7630	485	325	94	(1) dental office
L	Office	40	1601	27	7156	471	524	353	(4) office tenants
M	Food Service	68	2323	25	6960	423	1521	463	(17) food service (4) retail vendors

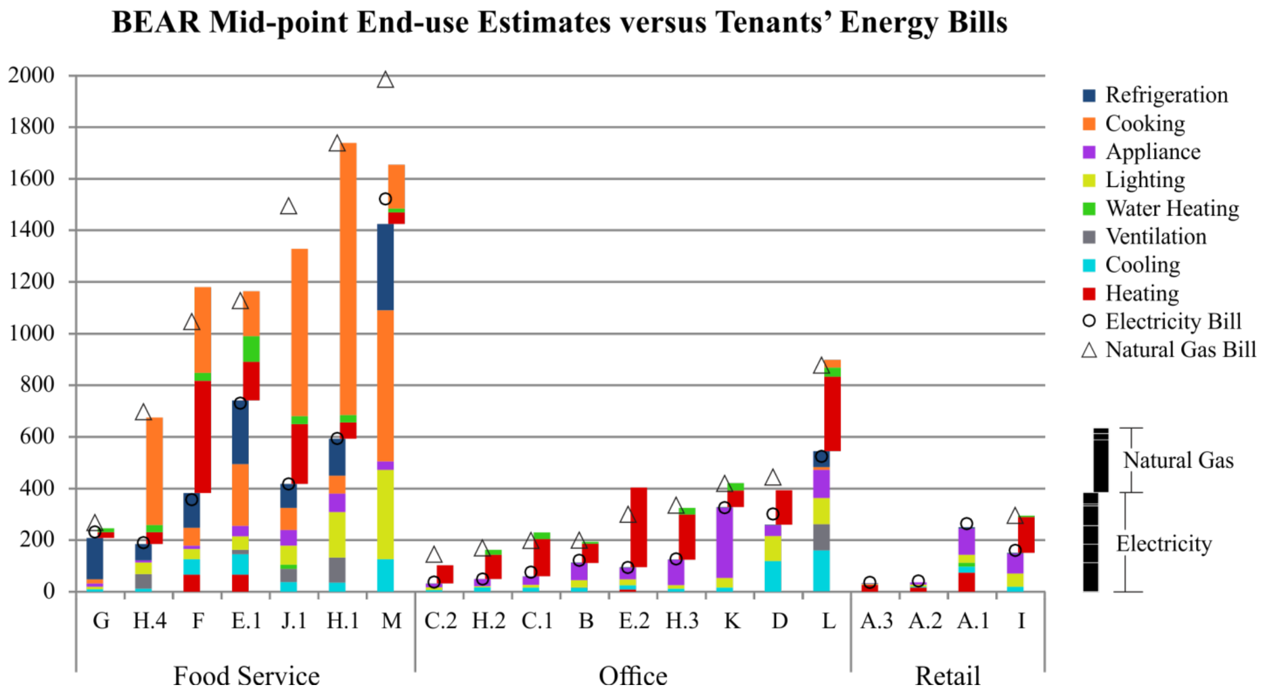


Figure 24. Cumulative results of BEAR, comparing mid-point annual energy consumption (i.e. electricity and natural gas) with annual energy bill consumption. Tenants are organized by commercial group and then in their increasing order of total annual energy bills.

To evaluate the accuracy of BEAR, energy bill data is compared with mid-point energy estimate (step 4), because the reconciled end-use energy data (step 5) is derived using tenant energy bills. Weighted averages of the absolute difference, termed *weighted average difference*, are used to evaluate accuracy of BEAR in terms of tenant energy bills. For the purpose of this article, *difference (%)* is the absolute value of the difference between the BEAR mid-point total estimate and a tenant's energy bill divided by the tenant's energy bill. Further, the *weighted average* refers to the influence of tenants' energy bills on the average of the *difference (%)* of all tenants, where larger energy consumers hold greater influence. Combined, these calculations compute the *weighted average difference*. Figure 24 illustrates the comparison between the mid-point annual end-use energy estimate and the total annual energy bills for each tenant.

6.5.1 BEAR demonstrated accuracy in estimating building-level energy bills

In general, BEAR displayed a total weighted average difference of 4.7% with electricity bills (standard deviation, $\sigma = 5.3$) and 13.3% with natural gas bills ($\sigma = 17.1$) for all tenants. In comparison, Lee, Yik et al. (2003) observed discrepancies greater than 15% in estimating electricity end-use consumption. Only tenant C.1 in the BEAR sample exhibited an error over 15% in electricity estimation. In terms of total energy consumption, BEAR exhibited a weighted average difference equal to 8.3% ($\sigma = 9.5$) for all tenants. BEAR exhibited an absolute difference equal to or less than 15% in 16 of 20 tenants for the combined electricity and natural gas estimation. A complete summary of results providing BEAR disaggregated end-use estimations and energy bill information per tenant is located in Appendices sections C.7 through C.9.

6.5.2 BEAR exhibited robustness in estimating food service and electric-only retail energy consumption

Research has focused on *office* building activities for benchmarking energy quantification methods, in part because of low uncertainty of operational parameters (i.e. rigid work schedules), affording office spaces with ample resources (Lanzisera, Dawson-Haggerty et al. 2013, Gandhi and Brager 2016, Gunay, O'Brien et al. 2016). A key design objective of BEAR is the ability to accurately portray end-use energy profiles for a comprehensive portfolio of building activities, termed *robustness*. To evaluate robustness, BEAR was implemented in food service enterprises.

Currently no publicly available method for quantifying commercial kitchen natural gas consumption has been established. As a first step towards rectifying this information gap, this study identified irregular modal fuel flow rates as a key roadblock. Many of the commercial kitchen equipment are manually controlled using valves, allowing the periodic, and potentially irregular, adjustment of fuel flow rate throughout a work day. However, the assignment of low, medium, and high “modal” flow rate ranges (i.e. each third of a turn on the dial) in addition to manufacturer data, facilitates the estimation of more accurate hourly operation within each modal range.

To illustrate, this process was implemented in tenants F, H.1, H.4, and J.1, each are full-service restaurants operating large natural gas equipment, e.g. griddles, ranges, and ovens. The average weighted difference in natural gas estimation for these tenants is 8.3% (σ = 7.2). In terms of total energy consumption, BEAR demonstrated accuracy to within a weighted average difference equal to 5.8% (σ = 5.6). These results suggest BEAR is capable of portraying commercial kitchen energy consumption, a needed resource in sector small commercial sector.

6.5.3 BEAR showed scalability in buildings of increasing size and complexity

Small commercial buildings range in size, i.e. floor area, and complexity, as a measure of the number of appliances and equipment operating within a building. BEAR was designed to be scalable; i.e. capable of accurately quantifying energy use in buildings of varying size and complexity. To assess this design objective, simple linear regression analysis was performed comparing the *difference (%)* with three factors: floor area, count of total components, and count of plug-in components (Figure 25**)**. A summary of component counts is available in Appendix C.10.

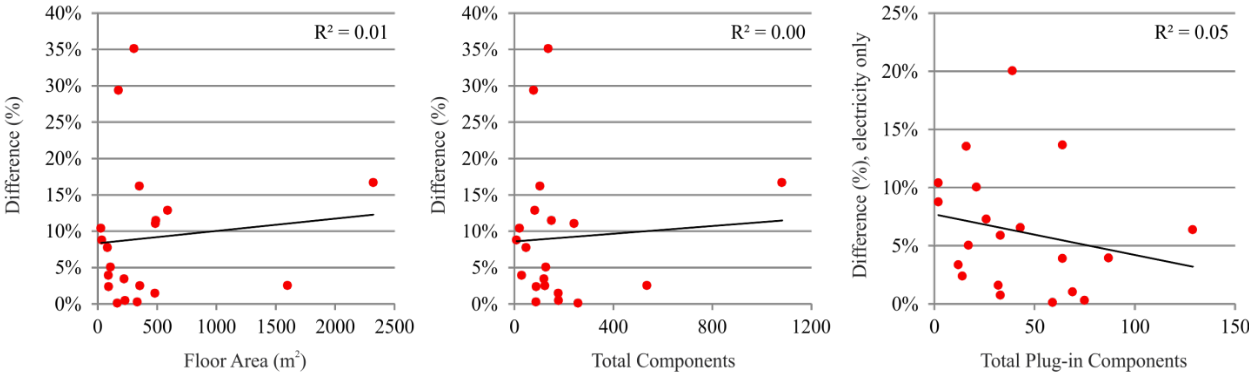


Figure 25. Simple linear regression graphs illustrating the relationship between three factors: building floor area (R^2 = 0.01), total components (0.00), and total plug-in components (0.05), and the difference between BEAR mid-point estimates and energy bills.

What is observed in the simple linear regression plots in Figure 25 is that neither a buildings floor area, the number of components (i.e. any energy consuming appliance, equipment or element in a building), or the number of plug-in components (i.e. electricity consuming appliances under end-uses of *appliance*, *cooking*, or *refrigeration*) explain the difference between BEAR's mid-point estimates and the collected energy bills. The results suggest BEAR achieves the desired scalability in the sample of buildings. However, there is still error which building activity, size or complexity, do not explain.

6.5.4 Uncertainty in BEAR estimates stem from two potential factors: seasonal loads and plug-in load assumptions

Two factors potentially resolve the discrepancy between BEAR and energy bills: (1) uncertainty in seasonal heating load estimation and (2) compounding error in estimating energy consumption of plug-in appliances. Figure 26 plots tenants' energy profiles (i.e. total energy consumed as a mix of electricity and natural gas) against the relative difference between BEAR’s mid-point and tenants’ energy bills, helping to visualize these two factors.

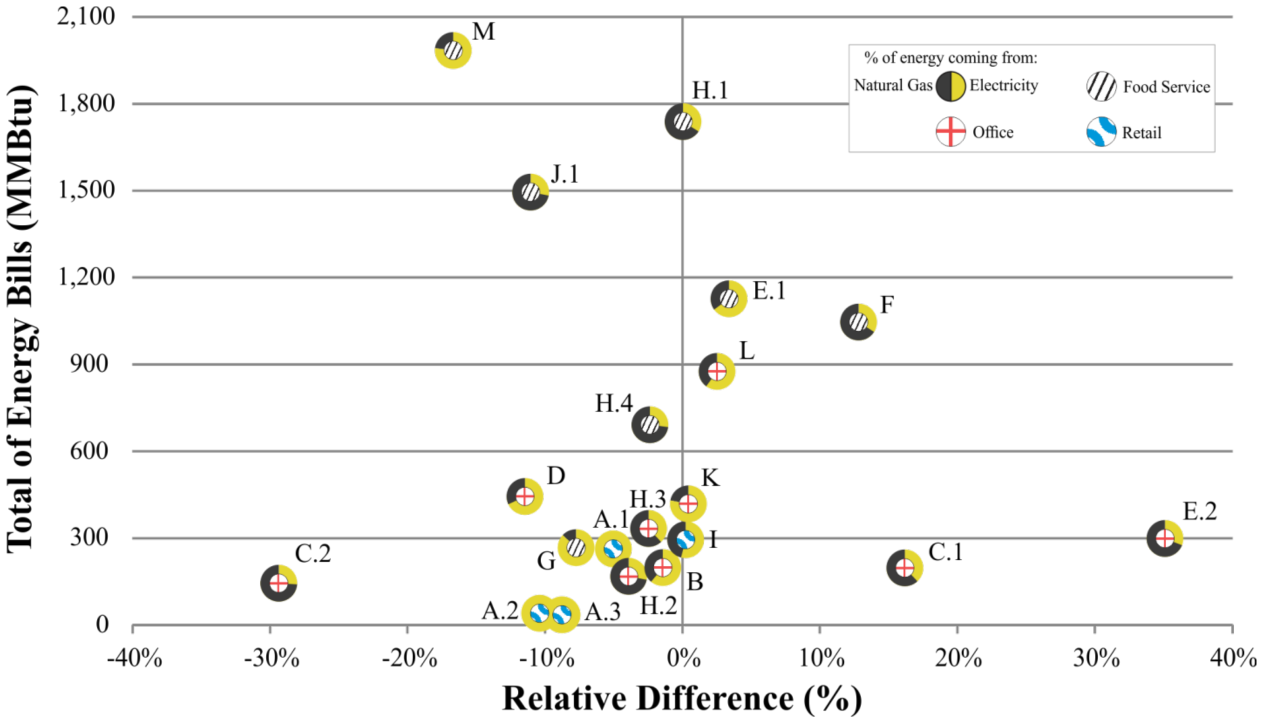


Figure 26. Illustration of tenants' energy profiles in terms of percentage from electricity and natural gas in relation to the relative difference between BEAR’s mid-point annual energy estimate and tenant’s total annual energy bill.

In comparing BEAR’s mid-point and reconciled estimate for heating and cooling end-uses, it is observed that heating load mid-point estimates were corrected by an average of 87 MMBtu, while cooling loads were corrected an average of 41 MMBtu. Further, simple linear regression (Figure 27) suggests that as the portion of total energy consumption attributed to heating increases so does the *difference (%)*. A larger sample is needed to verify this finding.

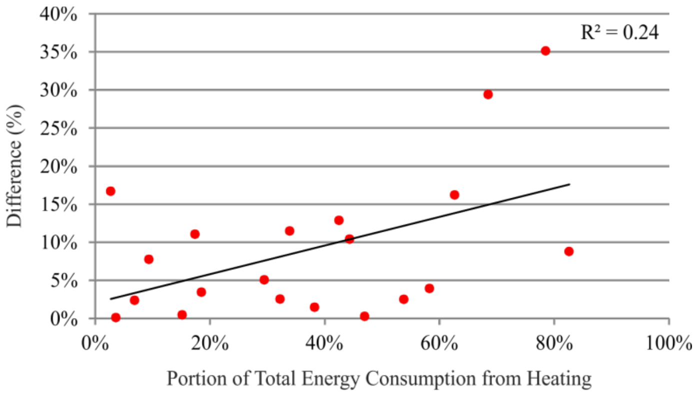


Figure 27. Simple linear regression analyzing the relationship of the space heating portion of total energy consumed in a tenant and the difference between BEAR mid-point estimates and energy bills.

However, the compounding effects of uncertainty in estimating plug-in appliance parameters, e.g. modal power and operation hours, may also explain error in estimates (Menezes, Cripps et al. 2014, Gandhi and Brager 2016). Plug-in appliances, for the purpose of this paper, include appliances in end-use categories of *appliances*, *cooking*, and *refrigeration*. Two scenarios stand apart: office computers in tenants E.2 and C.1 and plug-in cooking appliances in tenant M.

Computers and monitors were estimated to account for 30% and 18% of total mid-point estimated electricity consumption in tenants E.2 and C.1, respectively; while in tenant M, plug-in cooking appliances accounted for 41%. In either scenario, a key source of modal information is manufacturer labels, which may only provide voltage and amperes. Tenants E.2, C.1 and M exhibited among the highest *difference (%)*, potentially a result of the compounding effect of uncertainty in modal parameters. However, time-series energy data is needed to confirm this inference.

Collectively, these results indicate that BEAR has the potential to be an accurate, robust, and scalable resource, appropriate for use in a wide range of building activities, sizes and complexities. However, the sample of buildings a part of this study is small, and the continued use of BEAR would further define limitations or applications. Further, a smart meter study is needed to measure the effects of modal parameter uncertainty in estimating appliance energy use, subsequently informing seasonal load estimation error adjustments.

6.6 CONCLUSION

A bottom-up disaggregation approach was developed and implemented in thirteen buildings. The building energy assessment resource (BEAR) integrates energy algorithms and existing energy estimate resources into a single suite of resources. BEAR is intended as a mechanism for the delivery of energy information that addresses informational and indirectly financial barriers experienced in the SCB sector. Results for the efficacy of BEAR reveal a weighted average difference for electricity and natural gas estimation in all buildings of 4.7% and 13.3%, respectively. BEAR's design objectives of accuracy, robustness, and scalability were assessed. Discussion of BEAR's potential broader impacts from a bottom-up resource is presented and includes: (1) a method for estimating commercial kitchen natural gas use and (2) a repository of energy information.

The food service sub-sector is the largest end-user of energy in small commercial buildings (U.S. EIA 2012), and is heavily reliant on commercial natural gas cooking equipment. While other publicly available programs have yet to adapt modeling to meet food service demands, BEAR's bottom-up disaggregation method shows promise with an average weighted difference of 12.8% for natural gas mid-point estimations. Moreover, 20% of SCB natural gas consumption occurs outside space heating and water heating end-uses, predominately in building activities including food sales, inpatient health care, religious worship and strip malls. BEAR potentially spans across the SCB sector and advances research attempting to address non-seasonal, non-uniform natural gas consumption.

Disparity in existing energy resources is evident in their specificity of intended use as well as their web-based residence. BEAR aimed to assemble credible resources into a collective suite, providing users with a single resource capable of estimating energy consumption at the whole-building scale. Results indicate that BEAR is capable of estimating energy consumption in small commercial buildings when used by a trained professional. However, the question that remains, as with any energy resource, is if BEAR is a practical resource for use by SCB stakeholders. Answering this question requires placing BEAR in the hands of real building stakeholders and asking them to perform an assessment to reveal limitations in use of BEAR.

Future work will focus on the adaptation of BEAR for use by policy makers, energy service providers and energy conservation organizations to widen the marketability. Therefore, a next step is establishing collaborations with industry partners to implement BEAR and expand the portfolio of buildings currently studied. Further, a follow-up study will explore plug-load modal operational parameters (e.g. power and time in mode) to measure sensitivity of end-use energy profiles.

7.0 SMALL BUSINESS ELECTRICITY DISAGGREGATION: WHERE CAN WE IMPROVE? TOWARDS INCREASED TRANSPARENCY OF APPLIANCE MODAL PARAMETERS

This chapter is a continuation of the previous Chapter 6.0, and explores BEAR at the component-level, analyzing the accuracy of the energy estimate resources integrated to BEAR in addition to the sensitivity of energy quantification results due to uncertainty of parameter assumptions. The research presented is intended as an article for submission to the journal *Energy and Buildings*.

Ketchman, K. J., Khanna, V., Parrish, K., and Bilec, M. M., (in progress). “Small Business Electricity Disaggregation: Where can we improve? Towards increased transparency of appliance modal parameters.” working paper.

7.1 INTRODUCTION

In the previous chapter, a whole building, bottom-up energy disaggregation resource was presented, termed the Building Energy Assessment Resource (BEAR). The development of BEAR was intended to provide the small commercial building sector with a single source of energy efficiency information.

The importance of BEAR is the development of a *publicly available energy disaggregation resource that can provide an under-served small commercial building sector with meaningful energy information leading to the appropriate allocation of limited resources in reducing energy consumption and costs*. However, an examination of BEARs quantification mechanisms is needed to identify sources of uncertainty and the magnitude of their effect on appliance-level energy quantification; thereby, enabling development of informative resources to overcome challenges of providing effective energy efficiency measures. If stakeholders are to make informed decisions about individual appliances, then BEARs effectiveness must be measured by its ability to accurately quantify appliance-specific energy consumption.

This chapter aims to examine one aspect of BEAR's efficacy through a comparative analysis between BEAR's mid-point energy estimates and outlet smart meter measurements of appliances in two enterprise types, food service and office. A review of appliance-level energy metering studies is provided including a review of protocols for collecting data through outlet smart meters. In section 7.3, a summary of the physical and operational characteristics of the participating enterprises is provided. Additionally, the bootstrap statistical method and development of energy contour plots used to evaluate the accuracy of BEAR are presented. In section 7.4 results will be discussed in the context of BEARs accuracy and practicality within the target audience of small commercial building stakeholders. Finally, conclusions will show that the bottom-up approach to energy disaggregation employed by BEAR is as accurate as the information provided from energy estimate resources and manufacturer specifications. Future work will explore the function of contour plots as an alternative method for demonstrating the relationship between power and operation through spatial representation, suited to visual learners (Sprehn, Kremer et al. 2013).

7.2 REVIEW OF APPLIANCE SMART METERING STUDIES

To evaluate electricity use in buildings, a wireless smart meter network can be used to record time-series energy data of appliances. The review that follows will discuss existing smart meter studies and their methods used to analyze data, followed by a review of energy metering protocols used in this study (Lanzisera, Dawson-Haggerty et al. 2013).

7.2.1 Appliance-level metering studies

While building activity may offer a level of expectation towards end-use energy profile, a buildings' energy use is a function of its occupants and the appliances with which they interact (Hong and Lin 2013, Gandhi and Brager 2016). In response, research has evaluated this interaction through appliance-level smart metering studies, documenting power demand and occupant usage for an array of appliances, including but not limited to: computers, office equipment, refrigerators, and audio/video equipment (Camilleri, Isaacs et al. 2006, Moorefield, Frazer et al. 2011, Menezes, Cripps et al. 2014). With appliance-level data collected, research evaluates appliance parameters (e.g. modal power and operation) to characterize electricity consumption patterns of building spaces or appliances (Camilleri, Isaacs et al. 2006, Hong and Lin 2013, Menezes, Cripps et al. 2014, Christiansen, Kaltschmitt et al. 2015, Gunay, O'Brien et al. 2016, Ouf, Issa et al. 2016) and to describe the influence of occupant behavior on electricity consumption (Roberson, Homan et al. 2002, Desroches, Fuchs et al. 2014, Zhao, Lasternas et al. 2014, Tetlow, van Dronkelaar et al. 2015, Gandhi and Brager 2016).

To make sense of the smart meter collected data, appliance-level studies employ histograms, cumulative distribution functions (CDF), and power demand profiles. Histograms and CDFs describe appliance usage patterns through frequency of power demand values, revealing modal power levels (Camilleri, Isaacs et al. 2006, Menezes, Cripps et al. 2013, Desroches, Fuchs et al. 2014). Using a refrigerator as an example, Camilleri, Isaacs et al. (2006) defines standby power to be the "value that occurs most often," and is identified at 17 watts, while active mode power is defined as the spike in frequency at the highest metered power, identified between 190 and 200 watts. However, histograms and CDFs are one dimensional in that they only infer modal power levels. To understand modal operation, i.e. when and at what power appliances are used, power demand profiles plot metered power readings over a 24-hour period depicting user influence on energy consumption, such as decreased power demand during lunch or over nights and weekends (Menezes, Cripps et al. 2013). Together, these plots provide detailed energy data on modal power and modal operation, enabling evaluation of energy consumption patterns in consideration of user interaction, and are employed in this research article.

To ensure the collection of representative samples of appliance energy data, this study adopted smart metering protocols outlined by Lanzisera, Dawson-Haggerty et al. (2013).

7.2.2 Smart metering protocols for effective collection of data

Lanzisera, Dawson-Haggerty et al. (2013) defines three key protocols for the effective collection of appliance-level data useful to this study, including: (1) the smart meter technology necessary to record data, (2) the length of the study period, and (3) the sampling interval of appliance data. A summary of protocols used in prior smart meter studies is provided in Table 14, including the purpose for collecting the smart meter data. From Table 14, it is apparent that studies attempting to assess appliance parameters have used a host of study period lengths (spot measurements to one year) and sampling intervals (30 seconds to 60 minutes). This section reviews the three protocols outlined by Lanzisera, Dawson-Haggerty et al. (2013) in the context of this study, using Table 14 as a reference for what has been previously done.

In terms of smart metering technology necessary to record data, advancements in metering technologies since 2013 have made wireless plug-load smart meters more accurate and accessible from a cost perspective. One system in particular, the Plugwise® smart meter system using Zigbee protocol wireless networking, has been deployed in other research and was selected for this study (Zhao, Lasternas et al. 2014).

Regarding the temporal parameters of study period length and sampling, Lanzisera, Dawson-Haggerty et al. (2013) conclude two months of data collection at 5-minute intervals is adequate for evaluation of energy load profiles. Data collection periods over two months, or sampling intervals less than 1-minute, increase data analysis costs while not proportionally improving data quality. Conversely, data collection periods less than 2-months or sampling intervals over 5-minutes may not accurately portray energy patterns of appliances.

Table 14. Summary of metering studies and the methods used to collect data. Note: studies are organized chronologically

Studies	Length of study period (weeks)	Interval (minutes)	Purpose for collecting smart meter data was to measure:
Roberson, Homan et al. (2002)	spot	0.5	Modal operation and power data of commercial computers
Camilleri, Isaacs et al. (2006)	52	10	Standby power consumption in residential appliances
Moorefield, Frazer et al. (2011)	2	1	Modal operation of office appliances
Desroches, Fuchs et al. (2014)	1 to 10	2	Modal operation and power data of residential computers
Menezes, Cripps et al. (2014)	3	1	Daily appliance power load profiles
Zhao, Lasternas et al. (2014)	3	5	Timestamped power data for appliance activity level
Christiansen, Kaltschmitt et al. (2015)	0.5	1	Appliance electricity demand during work and non-work hours
Dunbabin, Palmer et al. (2015)	12	2 and 10	Daily energy use of residential appliances and peak energy demand
Tetlow, van Dronkelaar et al. (2015)	1	6	Daily electricity use of appliances
Gandhi and Brager (2016)	27	15	Appliance power demand during work and non-work hours
Gunay, O'Brien et al. (2016)	8	60	Hourly power demand of appliances
Ouf, Issa et al. (2016)	4	30	Daily electricity use of appliances at the whole school-level

This study used the existing body of literature to design a smart meter experiment that contributes to the greater building science research community. A network of Plugwise® smart meters using Zigbee protocol wireless networking was installed in two tenants over the summer of 2016 to collect appliance-level energy information. Data was sampled at 5-minute intervals over the allowable timeframe determined by the enterprise owners; 2 weeks (food service) and 11 weeks (office). The limitation of the 2-week study length in the food service tenant is discussed in conclusions; although, the 2-week study length fits within previously published smart meter studies (Table 14).

7.3 METHODS

The intent of this chapter is to examine the efficacy of a bottom-up building energy assessment resource described in Chapter 6.0. The goal is to identify sources of uncertainty in energy calculations and measure the magnitude of their effect on BEAR's mid-point energy estimates. To complete this goal, smart meters were installed in two enterprises following previously described protocols and statistical methods were implemented to analyze and visualize results. This section will describe the physical and operational characteristics of the participating tenants, outline the implementation of smart meters, and present the statistical methods used to analyze collected data.

7.3.1 Participating enterprises

Two commercial enterprises, previously receiving an energy assessment using BEAR, volunteered to participate in this follow-up smart meter study. Enterprise A is a restaurant/bar, operating 7 days per week at 112 hours per week with two-floors covering a total floor area of 167 m^2. Employees begin food preparation at 10:00 AM each day with the restaurant opening at 11:00 AM and closing at 2:00 AM. The restaurant is located in the heart of the University of Pittsburgh campus making food sales dependent on university life, i.e. lower food sales over summer break.

Enterprise B is a landscape architecture firm in a 3-story, 480 m^2, owner-occupied building located in downtown Pittsburgh, PA. The enterprise consists of 11 full-time employees with average weekly operating hours of 50 hours. The enterprise incorporates sustainability into its mission statement, exemplified with a simple green roof tray system installed in 2007.

7.3.2 Implementation of Smart meter protocols

Plugwise® wireless smart meters were installed at electrical outlets to monitor electricity consumption of individual appliances or power strips. Data was recorded in 5-minute intervals in units of kilowatt-hours (kWh). The smart meters connected wirelessly to a USB flash drive through a Zigbee network and uploaded data directly to a data management and visualization program. Where power strips were monitored, a complete list of metered appliances was recorded (see Appendix D.1).

The decision to monitor power strips was two-fold. First, in some instances the individual appliances were also monitored creating redundancy, which provided validation of monitors' measurements. Further, redundancy provided an opportunity to evaluate the practicality of monitoring power strips as a means for reducing the number of smart meters and costs for future studies. Second, energy consumption of multiple appliances is additive, enabling the comparison of metered power strips and the summation of BEAR energy estimates for same power strip appliances. However, power strip energy consumption, commonly associated with a small LED lightbulb, was not extracted from the collected data because measurements of the power strip power demand were unavailable during the study period.

In Enterprise A, the smart meter study was conducted over the summer, during University of Pittsburgh's summer semester when the student population is greatly reduced. Smart meters were installed in the kitchen, at point-of-sale (POS) stations, and the manager's office, which housed audio and video equipment in addition to a work computer. Table 15 compartmentalizes the equipment into key taxonomic categories.

Table 15. Summary of items metered grouped into an appliance taxonomy.

Enterprise	Appliance Taxonomy	Count	Description of appliances
A	Audio/Video	4	amplifiers, DVR router, cable box
	Commercial Food Handling	3	food warmers, freezer
	Accent Lighting	1	neon bar sign
	Networking	3	internet router, modem, Ethernet switch
	Personal	2	personal device charger
	POS Station	5	cashier monitor, printer, credit card reader
	Workstation	3	computer monitor, computer tower, UPS
B	Office Food Handling	6	microwave, toasters, coffee makers, refrigerator
	Task Lighting	1	desk lamp
	Workstation	15	computer monitors, computer towers

Smart meters were installed in Enterprise A at the start of business on Monday, July 11, 2016 and uninstalled on Wednesday, July 25, 2016, collecting data for 11 weekdays and 4 weekend days. The smart meters were left in place through the recording period, with data retrieved from the smart meters weekly. Partial days of data, specifically the install and uninstall dates, were removed from analysis because they were not complete days of data collection. The commercial refrigeration appliance, a 1 m^3 freezer, tripped an internal breaker in the smart meter, shutting off recording after one and half days of data collection, and was not restarted due to safety concerns.

The smart meters were installed at Enterprise B Wednesday and Thursday, August 17 to 18, 2017 and uninstalled on Wednesday, November 2, 2017. Several disruptions and office scenarios led to the removal of data, including a storm event which interrupted power to the smart meters over 4 days, an employee took vacation time over 12 days, and unmonitored days due to a malfunction in the smart meters. The smart meters were grouped into two rooms: kitchenette and office. A total of 73 full days of data were recorded for the office, including 53 weekdays and 20 weekend days, and a total of 75 full days of data for the kitchenette, including 53 weekdays and 22 weekend days. Table 15 includes a summary of items metered.

Weekly visits to the enterprises to download data and visually inspect the monitors provided the opportunity to identify changes to the appliances associated with each smart meter. At Enterprise A, no changes were recorded over the 15 days of recording. At Enterprise B, *Desk 4* computer tower was upgraded to a higher efficiency unit midway through the monitoring. Effected smart meters (*Desk 4* and *Desk 4 Tower*) were partitioned and assigned an “a” identifying pre-upgrade data, and a “b” for post-upgrade data.

7.3.3 Bootstrap Analysis

Bootstrapping is a statistical method used to estimate a population parameter by resampling with replacement from a sample of known values. Data for the 28 smart meters across both enterprises were organized by weekday and weekend and then by business hours and non-business hours to compare daily mean average energy consumption with BEAR’s weighted average daily energy consumption estimate and to estimate active mode power demand during business hours. Bootstrap resamples, of the same equal size as the smart meter dataset, were constructed using the 5-minute interval data at 1,000 iterations with the mean of each bootstrap resample calculated. Therefore, the mean represents the average 5-minute energy consumption of an appliance and is easily scaled to daily energy consumption or converted to power demand.

BEAR algorithms use modal power and operation to quantify daily and annual energy consumption. To compare with bootstrap resample results, a weighted average power demand for BEAR ($P_{BEAR.wt.avg}$) for the metered appliances was calculated by adding the product of each modal power (P_{mode}) and operating hours (H_{mode}), then dividing by the sum of operating hours equal to 24 hours in a day, see equation 4. This produced comparable power demand for each appliance and was additive when appliances were metered through a power strip.

$$\boldsymbol{P_{BEAR.wt.avg} = \sum(P_{mode} \bullet\ H_{mode}) \div 24} \qquad \textbf{Equation 4}$$

However, the influence of modal power and operation is indeterminable in the bootstrap mean daily energy consumption and the BEAR weighted average daily energy consumption. To evaluate modal power and operation independently, cumulative distribution functions and averages of daily operating hours from the collected timestamped smart meter data were compared with BEAR estimates.

7.3.4 Energy Contour Plot Development

One research goal was to evaluate BEAR's practicality in terms of building stakeholders' implementation, where direct comparison between BEAR estimates and bootstrap mean of the measured data evaluated the accuracy of BEAR estimates. To illustrate the usefulness of BEAR, energy contour plots were created containing the combination of possible energy consumption values that might be estimated by building stakeholders through application of readily available power and operation information.

To calculate the dependent variable, daily energy consumption (Wh), two matrices were constructed for power (W) and operation (hr) using the BEAR estimations for the active mode. To determine the power matrix, the maximum potential power demand for each appliance was identified either through manufacturer specifications or multiplying voltage (V) and amp (A) found on the manufacturer label. Then, starting from the BEAR estimated power demand for the determinant mode 20% increases and reductions were added until reaching the maximum power (V x A) and minimum power (0 W).

The operation matrix consisted of one hour intervals from 0 to 24 hours, where low and off operating modes were adjusted when active mode operation varied from the BEAR estimate. When the matrix operation hours of the active mode were less than the BEAR estimate, the difference in hours were added to the off-mode calculation parameter, providing the most conservative accounting. As matrix active mode operation hours exceeded the BEAR estimate, the low mode was reduced before reducing the off mode operational hours. This assured that each appliance accounted for 24 hours of operation.

Contours were calculated as a percentage change from the bootstrap mean of measured daily energy use. Contour lines were set at -50%, 0%, and 100% with additional 100% increases to 900%, the limit of the program used to calculate. Each contour line represents the possible combination of power and operation that equates to the level of energy consumption.

Energy contour plots plotted the daily energy consumption matrix calculated from the product of the power and operation matrices, where the x-axis is power demand and y-axis is operational hours. Thus, the energy contour plots contain the limits of daily energy use, allowing for visual evaluation of BEAR estimates and smart meter measured data, in the frame of energy estimation limitations.

7.4 RESULTS & DISCUSSION

In this section, results of the smart meter data analysis are presented, first assessing the accuracy of BEAR's daily electricity use estimate and then examining the appliance modal parameters constituting electricity consumption. Lastly, energy contour plots are presented as a means of increasing transparency of appliance electricity consumption through transformation of manufacturer labels and specifications..

7.4.1 BEAR is capable of providing stakeholders' with meaningful energy information

The bootstrap mean daily energy use, calculated from smart meter data, shows discrepancy with the BEAR weighted average daily energy use, calculated from the estimated parameters entered into BEAR during the energy assessment. An average difference – equal to the absolute value of the difference between the BEAR weighted average daily energy use and bootstrap mean daily average divided by the bootstrap value – of 67% for weekdays and 51% for weekends (Appendix D.2) was observed; the *12-cup Coffee Maker* accounted for nearly half of weekday difference, but consumed less than one quarter of a percent of total power demand and was removed from results. Other smart meters exhibiting large (greater than 100%) discrepancy include the *Three Pot Warmer*, *POS Monitor (bar)*, *Kitchenette*, and *Desk 4 Monitor*.

It should be noted that prior research assessing BEAR at the building-scale demonstrated accuracy to within 5% of electricity bills, with the average tenant using approximately 30 appliances at an estimated 31% of total electricity consumption (Ketchman, Khanna et al. 2017 submitted). In the context of this study, the observed average difference of 67% in individual appliances would impact building-scale estimation by 8%, meaning BEAR's whole-building energy disaggregation approach remains effective in delivering meaningful information to building stakeholders.

Discrepancies in appliance electricity estimations arise from uncertainty in estimating appliance modal power and modal operation parameters. An intensive analysis of the collected smart meter data was used to diagnose discrepancy between BEAR and the smart meter measurements.

7.4.1.1 Granularity of modal power information improves energy estimates

To evaluate uncertainty in the power parameter, CDFs were constructed with two representative plots illustrated in Figure 28. In the *Desk 6* CDF, sharp increases in cumulative probability suggest sustained power levels at 32 W and 120 W indicating two active power modes, because EnergyStar certified desktops must not exceed a maximum sleep mode power demand of 11 W (Energy Star 2014). The 32 W power level is attributed to desktop remote connectivity over nights and weekends (see Figure 29), noting that employees shut off monitors at the end of each workday. The 120 W power level is attributed to two monitors, equal to 21 W (similar to *Desk 4 Monitor* in Appendix 3), and the computer tower equal to the remaining power demand of 99 W. Therefore, the 32 W power level is considered a mid-active power level, meaning it is greater than the expected low mode of 11 W, but less than the recorded active mode of 99 W. Moreover, the maximum power potential for Desk 6 is 470 W – two monitors at 75 W each and the tower at 320 W – meaning that there are possibly unobserved power levels up to 470 W.

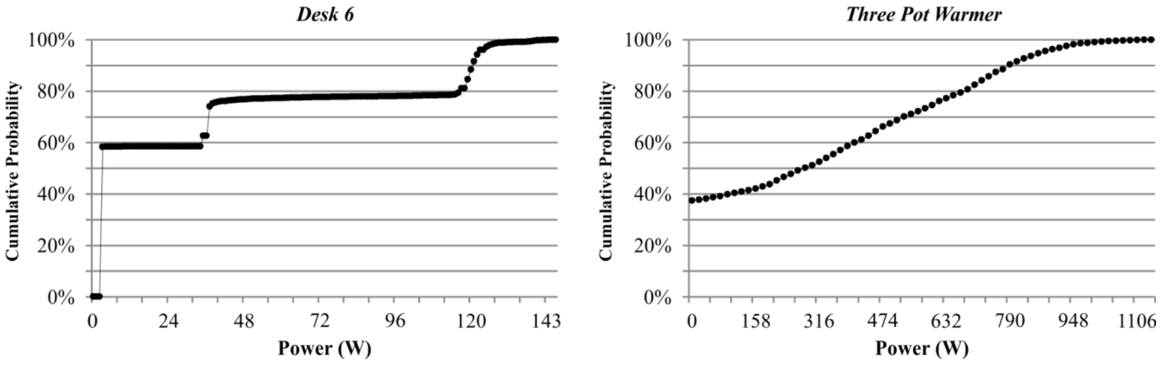


Figure 28. Cumulative distribution functions for *Desk 6* and *Three Pot Warmer*. *Desk 6* is a power strip containing two monitors and one computer tower.

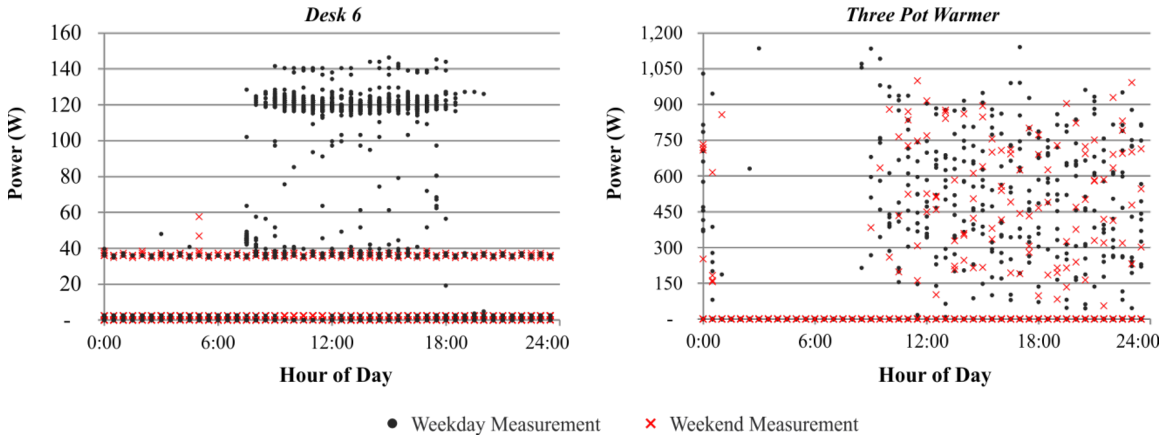


Figure 29. Power demand profiles in 30-minute increments for *Desk 6* and the *Three Pot Warmer*.

The *Three Pot Warmer* CDF depicts a distributed probability with no delineated power modes. The warmer operates using a manual control and oscillates electric current to a resistance coil to maintain desired temperature, resulting in varied power demand, as illustrated in Figure 29.

Assumptions must be made when entering modal power estimates to BEAR. For *Desk 6*, the active power mode was set at 69 W, as determined using energy estimate resources. For the *Three Pot Warmer*, the maximum power of 1200 W was used for active mode, under the assumption that the food warmer was manually operated at the highest temperature setting. It was determined the most effective way to assess uncertainty in power estimates was to perform, a bootstrap analysis of power measurements taken during business hours when appliances are most likely to be in active mode and compare results against BEAR active mode inputs.

Appliance power estimates in BEAR are derived from two sources: (1) manufacturer data and (2) the assembled energy estimate resources. Notably, when modal power information was available from manufacturer data, typically for electronic appliances, or from energy estimate resources, an average difference of 46% was observed between BEAR and bootstrap mean active power estimates. When modal information was not available, the maximum power was used for active mode point estimate, resulting in a difference between BEAR and bootstrap results of 416%. These results stress the importance of detailed modal information, including mid-active modes, because even in situations where modal information was available the median difference was 36%.

Observed in the smart meter data are two types of CDFs for power: (1) steps in probability indicating potential mid-active power modes and (2) an even distribution of power demand suggesting no delineation of modal power. Following previous research by (Wilkins and Hosni 2011, Menezes, Cripps et al. 2014), BEAR used three power modes, active, low and off, in energy estimation algorithms. However, results suggest three modes may be insufficient for some appliances, while in others a single average power demand may be more appropriate. Using cumulative distribution functions of power demand an appliance taxonomy may be derived, creating archetypal appliance categories with determined necessary modal power data for accurate calculation of energy consumption, similar to the two distributions discussed.

7.4.1.2 Building stakeholder knowledge can improve modal operation estimates

Smart meter data reveal limited discrepancy with the combined BEAR estimated daily total active and low mode operation; illustrated in Figure 30. The summation of active and low power modes was used, because an exact delineation between low and active power modes was not discernable from the smart meter data. Time stamped measured power demand from smart meter recordings offered insight for when appliances were being used, i.e. business hours, or were turned off, i.e. overnight. *The largest error in estimating operation hours occurred in Enterprise B, where employees connect remotely to their computers, which must be left on to connect. Remote connection increased daily weekday operating hours by as much as 40% for* *workstations connecting remotely over Desk 4 which did not connect remotely*. Further, employees connected remotely over weekends with greater occurrence than assumed in BEAR, which considered weekend remote connectivity to be negligible and was accounted for by adding to weekday operational hours. As depicted in Figure 30, this approach was not successful in accounting for weekend operation of workstations at Desk 1, 3, 5 and 6.

In Enterprise A, error in operating hour estimation is attributable to collection of incorrect data. The assumption that some appliances were turned on at 8:00 AM, when chefs arrived to begin food prep and remained on until the end of business at 2:00 AM the next day, 18 hours, was incorrect. The appliances of concern include the three pot warmer and neon welcome sign.

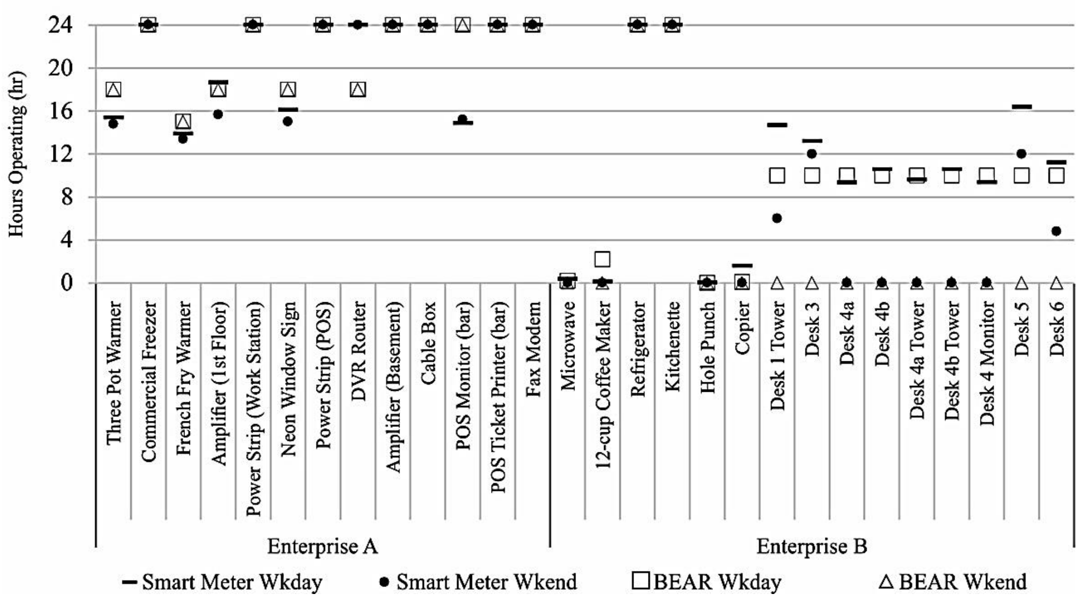


Figure 30. The average daily operating hours for appliances at each smart meter when operating in low or active modes.

Although energy estimate resources may provide typical annual operational hours, in-house employee and building stakeholder knowledge contains the most accurate estimates.

Fortunately, the corrective action for improving estimation is to put BEAR in the hands of the building stakeholders, as is the intent, where better information and knowledge exists and does not need to be transferred through a third party. However, for third parties attempting to use BEAR, care should be taken to collect the most accurate data, as is the case in any energy audit.

7.4.2 Energy contour plots illustrate the relationship between power, operation, and energy use

Energy contour plots were constructed (Appendix D.4) for a representative sample of the study group including kitchen and audio/video appliances from Enterprise A, and workstation power strips from Enterprise B, with the purpose of increasing transparency of appliance energy consumption through visual communication; a sample is provided in Figure 31. Within the energy contour plots, BEAR estimated weekday daily energy use is plotted as a single point, denoted by the intersection of the dotted lines, and the bootstrap mean of measured weekday daily energy consumption is plotted as the 0% contour line. Additionally, values extracted from the cumulative distribution functions (watt) and modal operation data (hour) were used to estimate the coordinate location, called the *Measured Estimate*, along the 0% contour line of an appliance.

The *Measured Estimate* represents the current actual appliance electricity profile with points to the upper right indicating increased operation and power, and points to the bottom left indicating decreased operation and power from the current actual use, and can be used to estimate changes in employee function. When using the energy contour plot prior to purchase, a consumer might estimate their operation, having an expectation of use, and then consider the function of the appliance (i.e. computer gaming versus word processing) as an indicator of power demand, which could be provided by manufacturers or through energy estimate resources, such as Energy Star's product database (Energy Star 2016). The energy contour plots contain all combinations of power, from zero to volt times amp, and operation, zero to 24 hours, but without accurate operation and power data, electricity estimations can differ from actual use, as depicted in Figure 31.

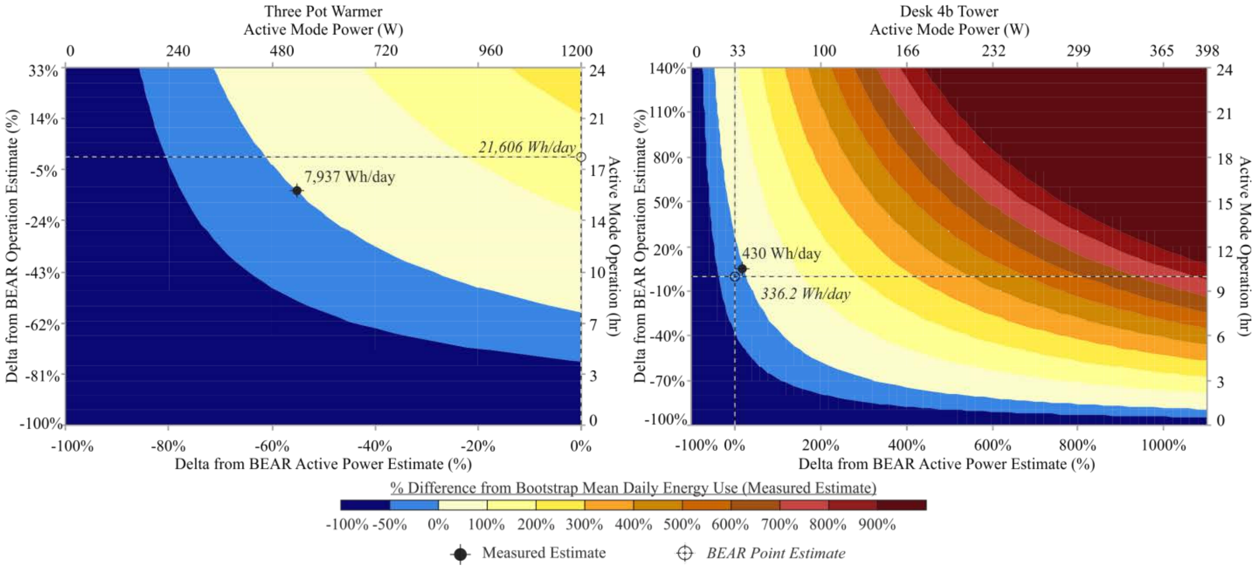


Figure 31. Energy contour plots illustrating potential electricity consumption values for *Three Pot Warmer* (left) and *Desk 4b Tower* (right), including the bootstrap mean daily energy use (Measured Estimate) and the BEAR daily energy estimate (BEAR Point Estimate). Note: the left vertical axis is the percent change from BEAR's estimated active mode operating hours with the right vertical axis depicting the corresponding active mode operating hours; the bottom horizontal axis is the percent change from BEAR's estimate active mode power (W) with the top horizontal axis depicting the corresponding active mode power (W); the contours represent the percent change from the *Measured Estimate* contour line at 0%; together the axis represent the change necessary in BEAR's estimated parameters to meet the 0% contour line while the contours represent the percent difference in energy consumption between BEAR's estimate and the *Measured Estimate*.

7.4.2.1 Error in x-axis (power) drives error in quantifying energy consumption

What is perceived from the energy contour plots is the distance along the x-direction in relation to y-direction, signifying that an improper assumption of modal power has a larger impact on energy quantification than operation. The data supports this notion. If power assumptions were corrected to match measured data, a 59% improvement in BEAR estimates for all appliances would be observed, leading to an average difference in energy estimates between BEAR and bootstrap results of 22%.

However, correcting modal power inputs used in BEAR is difficult, as modal power is derived from manufacturer specifications and energy estimate resources. It is at the discretion of the manufacturer to provide electrical information beyond volt and amp of an appliance, and energy estimate resources use scientifically calculated generalizations to simplify calculations for use by the public. Yet, even the provision of sleep, low and active mode power information may not be enough in some appliances where function plays a large role in power demand, exemplified in computers.

7.4.2.2 Error in y-axis (hour) is also influential in quantification accuracy

Energy contour plots revealed that BEAR estimates are within reason of providing meaningful energy estimates given building stakeholders deeper knowledge of appliance operation and employee function than the authors. Difference between the BEAR estimate and *measured* estimate in the y-axis suggests improper assumptions of appliance operational hours. As previously discussed the employees and building occupants will have improved knowledge of appliance operation. If operational estimates were corrected, the BEAR daily energy estimates would have improved on average by 25%, leading to an average difference in energy estimates between BEAR and bootstrap results of 76%. Most notably, BEAR estimates for the remote connecting workstations, *Desk 1 Tower*, *Desk 3*, *Desk 5* and *Desk 6*, would have improved by 48%. While it is expected that building stakeholders have greater awareness of daily operations, access to modal power information is less plausible.

The energy contour plots provide a means of visualizing the relationship between power, operation, and energy consumption in individual appliances. The value of these plots lies in their ability to convey uncertainty in assumptions to both research and building stakeholder communities through either vector analysis or optical spatial estimates. Energy contour plots could be a powerful informational tool easily adopted by certifications, such as EnergyStar, or manufacturers to communicate energy efficiency of products. With applications beyond appliances, energy contour plots could be adapted to represent all the possible combinations of energy use at the whole building scale, capable of plotting a path towards zero energy use.

7.5 CONCLUSION

In this study, a comprehensive examination of a building energy assessment resource to evaluate the accuracy of energy quantification methods and the sources of uncertainty was performed. Using smart meters, 5-minute interval data was recorded for appliances in two enterprises, (A) restaurant/bar and (B) landscape architecture firm, over 15 and 73 days, respectively. A bootstrap statistical method was used to estimate mean power and energy consumption organized into weekdays and weekends. Cumulative distribution functions, weighted averages and energy contour plots were created to quantify error in the power and operation parameters and to evaluate their impact on BEAR’s energy quantification.

Results of the analysis reveal that BEAR is capable of providing building stakeholders with meaningful energy information. Modal operation was observed to be an important factor in energy quantification and was reliant on detailed data collection. Notably, addressing error in modal **operation** does not require alterations to BEAR's components, because enterprises have access to more accurate information than the authors in this study. A 25 percent reduction in the average difference of energy quantifications was possible through improvement of modal operation assumptions alone.

To address uncertainty in estimating modal power, which accounted for 59% of BEARs difference with smart meter data, the authors suggest addressing manufacturer labels or specifications through improved information transparency. This might include functional power data, such as central processing unit power input relative to software installed on a computer. Cumulative distribution functions revealed multiple mid-active modes in computers and other appliances; the *DVR Router* contained four distinct mid-active modes. Alternatively, energy contour plots could be deployed on packaging or websites to enable quick spatial analysis of energy consumption at varying combinations of power and operation, which may be better suited for visual learners who rely on spatial relationships to retain and recall information (Sprehn, Kremer et al. 2013).

Energy contour plots may employ several methods to help visualize data: (1) vector distances can be used to measure change in energy consumption, (2) appliances of similar type can be compared in one figure, and (3) benchmarks for appliance function may be plotted to illustrate how function impacts energy use. The computer industry would be a logical early adopter as their appliances are heavily impacted by function as seen in this and other research (Desroches, Fuchs et al. 2014, Menezes, Cripps et al. 2014).

Future considerations for this study include the expansion of energy contour plots to a web-based application where users could scroll over the plot to reveal power, operation and energy use data. A next step may be to include employee function and software performance metrics to increase the readability of plots for use by building stakeholders. The potential scaling up of contour plots to visualize whole-building energy use would have novel applications in energy districts or the real estate market. Additionally, energy disaggregation research should allocate resources towards bottom-up disaggregation of natural gas equipment, which would improve accuracy of disaggregation methods but more importantly open the door to the food service sector.

8.0 CONCLUSIONS

By the end of the century, global temperature rise is likely to exceed 1.5 °C relative to 1900, a change that will elicit ecological degradation, threaten food security, and increase urban system vulnerability (IPCC 2014). While anthropogenic greenhouse gas emissions are certain to impact global warming over the next century, to what extent is governable provided societal, economic, and ecological reforms instilled through education and empowerment of global communities.

In response, efforts to combat the impacts of global warming have formed around the building sciences, in particular energy efficiency in the built environment. Buildings represent 40% of national annual primary energy consumption and 34% of national greenhouse gas emissions (U.S. EIA 2012, U.S. EPA 2016). The community interconnectedness concept presented in this dissertation was developed to highlight the interconnectivity of three learning communities, *Student*, *Homeowner*, and *Small Commercial*, which represent the present and future of building ownership, design and operation. Through systems-thinking, these learning-communities may be organized to form a larger learning-network, capable of providing formal and informal learning through pedagogical design, interactive discussions, personalized energy reports, and technical informative resources.

Research questions were posed and objectives outlined, as follows:

Student learning-community:

(1) Can the NELC engineering education approach train and foster student learners and energy leaders? Does the collected data support the use of the flipped classroom and service learning?

(1b) How do student outcomes, in the context of sustainability, differ between approaches (stand-alone course versus senior design) to integration of sustainable engineering to curricula? What do these outcomes suggest for the continued integration of sustainable engineering to curricula?

Homeowner learning-community:

(2) Were the energy assessments and the proposed energy efficient measures effective in reducing residential energy consumption?

Small Commercial learning-community:

(3) Can a robust and technically sound program, modeled after the residential, be developed to reduce energy consumption in small commercial buildings?

Elements of this dissertation examined the three individual communities of the interconnectedness concept, in the context of a systems-thinking approach to educating building stakeholders. First, a survey of students participating in the NELC residential energy assessment flipped-class was conducted to evaluate their perceived benefits, finding statistical evidence to suggest students perceived an increase in confidence in course material. Second, an evaluation of student outcomes, in terms of sustainability, was performed in two course using different approaches to integrating sustainable engineering to syllabi, concluding that students in the stand-alone sustainable engineering course performed stronger in application and analysis of sustainable engineering concepts than those in senior design course. Third, evidence was presented that suggests the traditional taxonomy of homeowner barriers and motivators is incomplete, illuminating the potential for re-exploration of barriers and motivators in the residential sector. Fourth, a robust and scalable energy disaggregation resource was developed and implemented in thirteen small commercial buildings in conjunction with smart metering in two tenants. Findings from these two research projects indicate that the bottom-up energy disaggregation method developed in this research is capable of providing the small commercial sector, as a whole, with a practical method for estimating end-use energy consumption in their buildings and tenant spaces. Moreover, the smart meter study illuminated a need for improved energy information readily available to those building stakeholders charged with making informed decisions on energy efficiency investments. A summary of project conclusions is presented below, followed by future work considerations.

8.1 LEARNING-COMMUNITY SUMMARY

In this section, a summary of research outcomes is presented for each of the three communities and associated research questions and objectives.

8.1.1 Student community

Two flipped-classroom courses part of the National Energy Leadership Corps energy assessment program were examined to answer research question (1) through objective (1.1):

Objective 1.1: Evaluate student perceived learning and classroom environment through three implemented evaluative methods 1) pre- and post-module confidence questionnaire, 2) final course reflection journaling, and 3) the College and University Classroom Environment Inventory (CUCEI).

Conclusions of the research establish students' perceptions of the flipped-classroom design in disseminating energy education, and poses positive student feedback towards longitudinal application of learned material. Results were presented at the 2014 ASEE Annual Conference and Exposition in Indianapolis, IN, and included in the conference proceedings (Marks, Ketchman et al. 2014).

To answer research question (1b), student projects collected from two years of senior design and stand-alone sustainable engineering courses at two universities were evaluated for sustainability content using a holistic sustainability rubric. The project followed objective (1.2):

Objective 1.2: Evaluate course projects for student outcomes, in the context of sustainability, at senior design and stand-alone sustainable engineering courses, using a holistic sustainability rubric, which incorporates cognitive assessment (Bloom's taxonomy), the quantity and interdependency of sustainability pillars incorporation, and additional metrics (Dancz, Ketchman et al. 2017 accepted).

The research demonstrated students' ability to achieve higher levels of cognition, in the context of sustainability, in the stand-alone sustainable engineering course projects over the senior design projects, in addition to increased linkage of the three pillars of sustainability at the stand-alone course. In conclusion, two possible reasons as to why students did not demonstrate greater knowledge of sustainability in senior design projects were postulated: (1) a 'packed' or 'full' senior design course and (2) expectations from instructors and rubrics may not contain clear elements of sustainability. These findings impact how ABET criteria are integrated to departmental curricula and how ABET criteria are assessed, i.e. course syllabus and instructor influence student outcomes.

8.1.2 Residential community

Over a five-year period, 120 energy assessments were completed by students through the NELC program. Approximately 600 energy efficiency measures were recommended. A post-assessment survey was delivered to 82 eligible homeowners, with 27 homeowners responding (33% response rate). Statistical analysis of participant responses was performed to answer the research question (2) following objective (2.1):

Objective 2.1: Implement a post-energy assessment survey of homeowners with the explicit goal of collecting energy bills and information on implemented energy efficiency measures since their energy assessment. Survey questions include::

- What energy efficiency measures (EEM) were completed since the assessment?
- Did the homeowner do the EEMs recommended in the report or did they do others?
- What is the homeowners' motivation for their decision to adopt or not adopt a recommended energy efficiency measure?
- Did their energy consumption change since implementation of EEMs according to standardized metrics (e.g. kBtu/HDD)

Objective 2.2: Analyze homeowners' responses to motivation questions using two-sample hypothesis test on the difference in proportions and chi-square test for independence to: (1) identify potential barriers to adoption of classifications of energy efficiency measures and (2) measure if adopted measures are perceived more favorably than non-adopted measures.

The holistic assessment approach implemented, strived to: (1) maintain a worldview-neutral approach to avoid alienating homeowners with strong values and tendencies, (2) adapt recommendations based on worldview, interests, and energy concerns of the homeowner, and (3) modify report style based on variable cognitive styles and worldviews of homeowners. Adoption of recommended EEMs, as reported by homeowners through the post-assessment survey, was measured at 30% of recommended energy efficiency measures, aligning with previous studies (Fuller, Kunkel et al. 2010, Ingle, Moezzi et al. 2012, Palmer, Walls et al. 2013, Murphy 2014). However, two key findings were identified.

First, energy conservation programs' reporting metrics should be standardized enabling innovation in program design through expansion of knowledge on the best practices in energy program design and implementation. Within that realm, catalytic impacts of the NELC approach suggest success in disseminating information through the energy report; however, it is not common practice to perform longitudinal studies to capture these secondary investments. By documenting this data, energy conservation programs could show measurable increases in adoption rates of efficiency upgrades, reinforcing the need for continued support of energy conservation programs. Recommendations to energy conservation programs or future building science research on the efficacy of energy audits should focus on these elements.

Second, homeowners self-identified and implemented comprehensive envelop energy retrofits (e.g. window upgrade from single pane to double) at a rate higher than adoption of recommended improvements. This suggests that the homeowners participating in the study were motivated to make comprehensive improvements, but the motivators and barriers incorporated to the post-assessment survey were not inclusive of the homeowners' true motivations or barriers. This led to the recommendation for the re-exploration of the traditional taxonomy of barriers and motivators, which will result in advancements in holistic energy audit design and demand-side energy reduction strategies.

8.1.3 Small commercial community

The small commercial building sector represents the overwhelming majority of commercial buildings (95% by number), and accounts for roughly 9% of national primary energy consumption (U.S. EIA 2012). A building energy assessment resource (BEAR) was developed and implemented in thirteen buildings to answer research question (3) and the following objectives (3.1) and (3.2):

Objective 3.1: Utilizing the residential framework, develop an energy assessment resource that can be used by small commercial building owners or tenants in evaluating their energy use at the building-scale or appliance-scale.

Objective 3.2: Implement the developed resource in a portfolio of buildings to discern the limitations of the resource in different commercial enterprises.

Objective 3.3: Using the collected building information implement a smart meter study to validate appliance-level estimations while also assessing the magnitude of effect uncertainty has on energy estimation and methods to address.

The use of BEAR at the tenant-scale resulted in a weighted average absolute difference between BEAR and electricity bills of 4.7% (standard deviation = 5.3 percentage points) and for natural gas bills 13.3% (17.1), in the 21 tenant spaces sampled. Major findings from this research reveal that BEAR is robust and scalable, two key features intended during the development process. Robustness was observed in the similar results when comparing food service tenants with office and retail. The average weighted absolute difference for electricity and natural gas in food service was 4.1% and 12.8%, respectively, which is comparable to office and retail tenants, which exhibited 6.0% and 14.6% in electricity and natural gas, respectively. Scalability was observed in the manner with which estimation error did not change with increases in floor area, i.e. building M was 241% larger than any other in food service and building L was 105% larger than any other in the office category. In combination, these findings make the BEAR approach an innovative step in energy quantification of buildings, primarily because of the flexibility with which BEAR may be used in a portfolio of enterprises and buildings sizes up to 50,000 ft^2.

A crucial aspect of BEAR is the ability to make targeted energy improvements in a building or space. To ensure the accuracy of information being transferred between BEAR and the user, an appliance-level study was conducted to evaluate integrated components. Results indicated discrepancy between BEAR and metered daily energy consumption, concluding that modal power and operation assumptions led to the discrepancy, but are addressable. First, modal power data is scarcely available for appliances, leading to the development of contour plots which illustrate spatial relationships between power (W), operation (hr) and energy (Wh), enabling consumers to quickly gauge energy consumption based on appliance function. Second, the research team made assumptions on appliance operation when information could not be obtained, but it is expected that building tenants would have more accurate information on operation schedules, improving energy quantification estimates. Improvements in the accuracy of power or modal data were shown to reduce relative error in BEAR energy estimates by as much as 63%.

8.2 CONCEPTUALIZING COMMUNITY INTERCONNECTEDNESS

Society faces challenges of increasing complexity as the world becomes decreasingly isolated. While anthropogenic greenhouse gas emissions are certain to impact global warming over the next century, to what extent is governable provided societal, economic, and ecological reforms instilled through education and empowerment of global communities.

This dissertation conceptualizes the interconnectivity of three learning-communities. This concept forms around the integration of flipped-class sustainable engineering education, focused on building energy science, with service-learning elements, intended to generate informal learning networks between students and communities. Leveraging the service-learning experience, building stakeholders from either the homeowner or small commercial communities, can be engaged through informative holistic energy assessments. Lastly, continued development of resources which address building stakeholder barriers to energy efficiency investments could be used to engage students in technical research while serving building stakeholders in need of practical and accessible energy information.

Collectively, these elements form a concept that could be implemented at academic institutions, or by using this dissertation, elements could be implemented through creation of multi-sector learning communities outside academia. Whatever the path chosen, the continuation of research should focus on progressing the concept community connectedness, because achieving comprehensive building energy reductions requires intercommunal collaboration.

The following sections conclude this dissertation by outlining future work that continues the learning community research.

8.2.1 Examination of sustainable engineering integration methods

The three learning-communities are interconnected through the temporal structure of life-long learning: starting as students, entering the workforce and becoming homeowners. Through each level, students bring with them their education and leadership. However, longitudinal studies are a significant gap in the engineering education community. Examination exploring questions of how much information students retain at different time scales after graduation, do students apply their energy efficiency knowledge in their personal lives, and what are the careers paths taken looking at different time scales after graduation. These questions embody the principle of *life-long learning,* self-regulation of continuous learning (O'Neill, Deacon et al. 2015). Identification of qualities exhibited by students which may indicate propensity for life-long learning may be discerned through longitudinal research, leading to advances in engineering education.

Future research should also examine other methods for integrating sustainable engineering to existing curricula, such as the module-based approach. Given that sustainable engineering deals in societal contexts, quantitative assessment of student outcomes in varying pedagogical approaches that provide students different learning experiences, i.e. active versus problem solving, would provide faculty with detailed tools for redesigning curricula to meet ABET and ASCE BOK2 requirements.

8.2.2 Collaboration with behavioral sciences in the residential sector

It is estimated that by 2025, utility customer-funded energy efficiency programs, natural gas and electric, will spend between \$6.5 and \$15.6 billion annually, with demand-side management planning accounting for a significant portion on the electric utility side (Barbose, Goldman et al.

2013). While any investment in energy efficiency may be considered positive, consider that the IPCC projects a minimum global temperature rise of 1°C by mid-century, threatening ecological degradation, food insecurity, and urban system vulnerability (IPCC 2014). Barriers exhibited in the residential community slow the diffusion of energy efficient technologies, in turn constraining greenhouse gas reductions. This research proposed the expansion of the traditional taxonomy of barriers and motivators to energy efficiency investments. As sustainable engineers we cannot expect to resolve these complex multidisciplinary problems. Moving forward, it is essential to partner with behavioral sciences in a cross-disciplinary collaborative effort, aimed at engaging homeowners' psyches where decisions making may occur without conscious awareness (O'Neill, Deacon et al. 2015). Moreover, development of a framework for the study of deep conscious decision making could be applied across building sectors, including small commercial. Such research has broad implications on energy efficiency program design, and allocation of resources at the national, state and local levels. Identification of building stakeholders' 'true' barriers or motivators would direct more meaningful outreach with the ultimate goal of reducing energy consumption.

8.2.3 Expansion of BEAR to Policy and Conservation Communities

BEAR was developed and intended for use by owners and tenants in small commercial buildings; however, there are an estimated 7 million enterprises within the small commercial building sector. Increasing the avenues by which these building stakeholders may connect directly or indirectly with BEAR will increase the opportunities for energy reductions within the SCB sector. Future work would focus on expansion of BEAR to incorporate policy makers, conservation groups and energy service providers to the list of intended users, as they represent a major consortium of energy funding and information in building efficiency. Steps to incorporating these groups may include development of a second version of BEAR specific to managing a portfolio of buildings. In addition, development of training modules will further efforts to install BEAR within the small commercial community, by providing guidance through the six steps of the BEAR model.

8.2.4 Introduction of appliance function to the energy contour plots

Electric appliance loads are expected to continue to grow in share of building energy consumption, illustrated by a 5% decrease in number of small commercial buildings without a computer and a 6% increase in the number of SCBs with a dedicated server between 2003 and 2012 (U.S. EIA 2012, Gandhi and Brager 2016). Replacement of these appliances over time will offer ample opportunity to increase energy efficiency in buildings, as newer appliances typically increase energy efficiency in meeting consumer interests, such as battery life or processor performance. The created contour plots could help to guide consumers towards appliances that best fit their intended function, such as in the computer market. Future work will look to introduce appliance function to the energy contour plots enabling comparison of energy consumption in terms of how an appliance will be used.

In whole, this dissertation has demonstrated that students, homeowners, and small commercial building stakeholders can be connected through innovative educational and informative methods as a means for reducing energy consumption in the built environment. The innovative methods employed in this research relied on collaborations between academia, industry, and public, and should not be discounted when attempting similar work in the future. However, the complexity of international issues posed by global warming and increasing entanglement of international societies will necessitate researchers look towards innovative intercommunal solutions at larger scales than posed in this research.

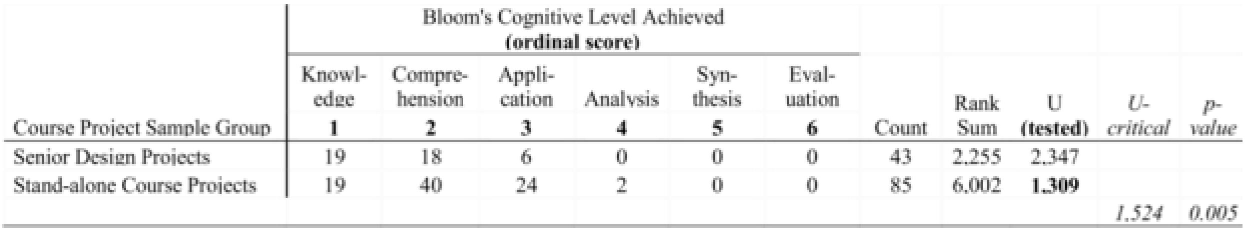
APPENDIX A

SUPPORTING INFORMATION FOR SUSTAINABLE ENGINEERING COGNITIVE OUTCOMES: EXAMINING DIFFERENT APPROACHES FOR CURRICULUM INTEGRATION

The tables included within this section present the results of statistical analysis performed on the projects sampled from the senior design and stand-alone sustainable engineering courses.

A.1 DISTRIBUTION OF RESULTS FOR BLOOM'S TAXONOMY

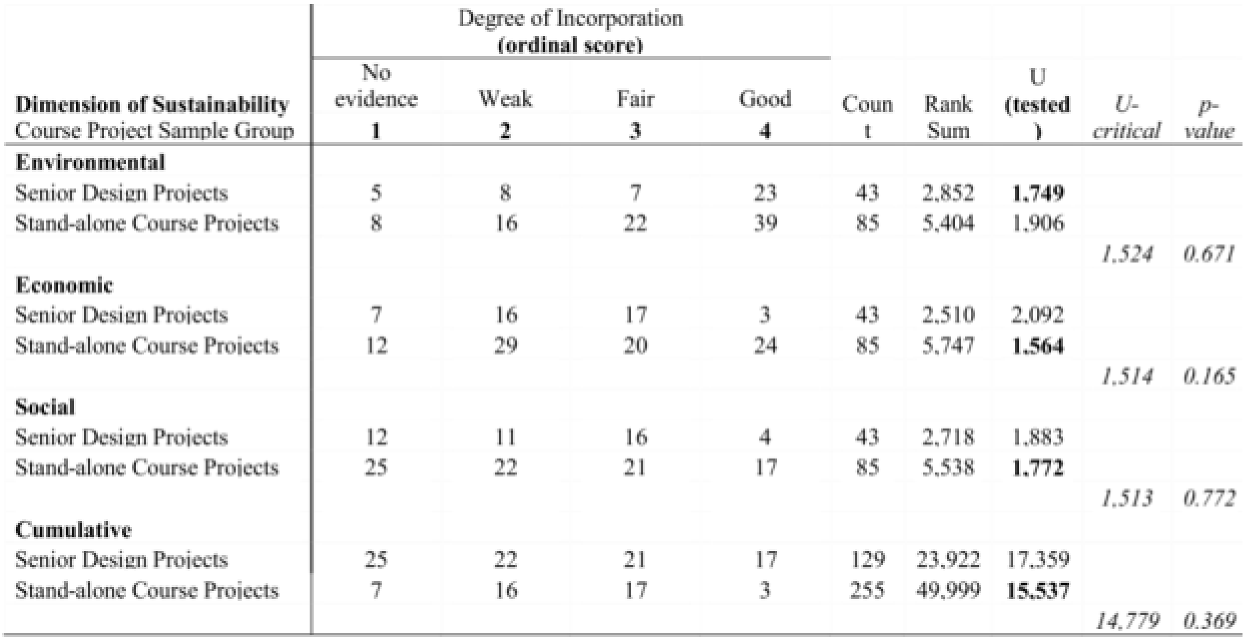
Distribution of *Bloom's Taxonomy* (Bloom, Engelhart et al. 1956) cognitive levels achieved by projects for the senior design and stand-alone sustainable engineering courses studied. Mann-Whitney U test results are included.



	Bloom's Cognitive Level Achieved (ordinal score)										
Course Project Sample Group	Knowledge **1**	Comprehension **2**	Application **3**	Analysis **4**	Synthesis **5**	Evaluation **6**	Count	Rank Sum	U **(tested)**	*U-critical*	*p-value*
Senior Design Projects	19	18	6	0	0	0	43	2,255	2,347		
Stand-alone Course Projects	19	40	24	2	0	0	85	6,002	**1,309**		
										1,524	*0.005*

A.2 DISTRIBUTION OF RESULTS FOR DIMENSIONS OF SUSTAINABILITY

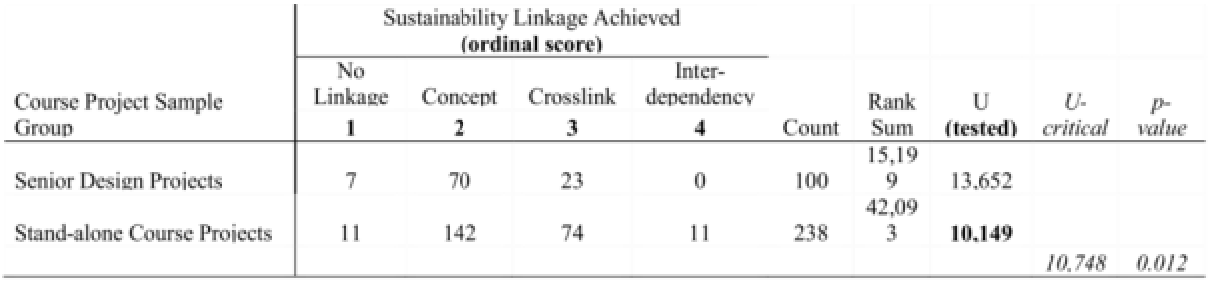
Distribution of *Dimensions of Sustainability* (Bielefeldt 2013) achieved by projects for projects from the senior design and stand-alone sustainable engineering courses studied. Mann-Whitney U test results are included.



	Degree of Incorporation **(ordinal score)**								
Dimension of Sustainability Course Project Sample Group	No evidence **1**	Weak **2**	Fair **3**	Good **4**	Count	Rank Sum	U **(tested)**	*U-critical*	*p-value*
Environmental									
Senior Design Projects	5	8	7	23	43	2,852	**1,749**		
Stand-alone Course Projects	8	16	22	39	85	5,404	1,906		
								1,524	*0.671*
Economic									
Senior Design Projects	7	16	17	3	43	2,510	2,092		
Stand-alone Course Projects	12	29	20	24	85	5,747	**1,564**		
								1,514	*0.165*
Social									
Senior Design Projects	12	11	16	4	43	2,718	1,883		
Stand-alone Course Projects	25	22	21	17	85	5,538	**1,772**		
								1,513	*0.772*
Cumulative									
Senior Design Projects	25	22	21	17	129	23,922	17,359		
Stand-alone Course Projects	7	16	17	3	255	49,999	**15,537**		
								14,779	*0.369*

A.3 DISTRIBUTION OF RESULTS FOR SUSTAINABILITY LINKS

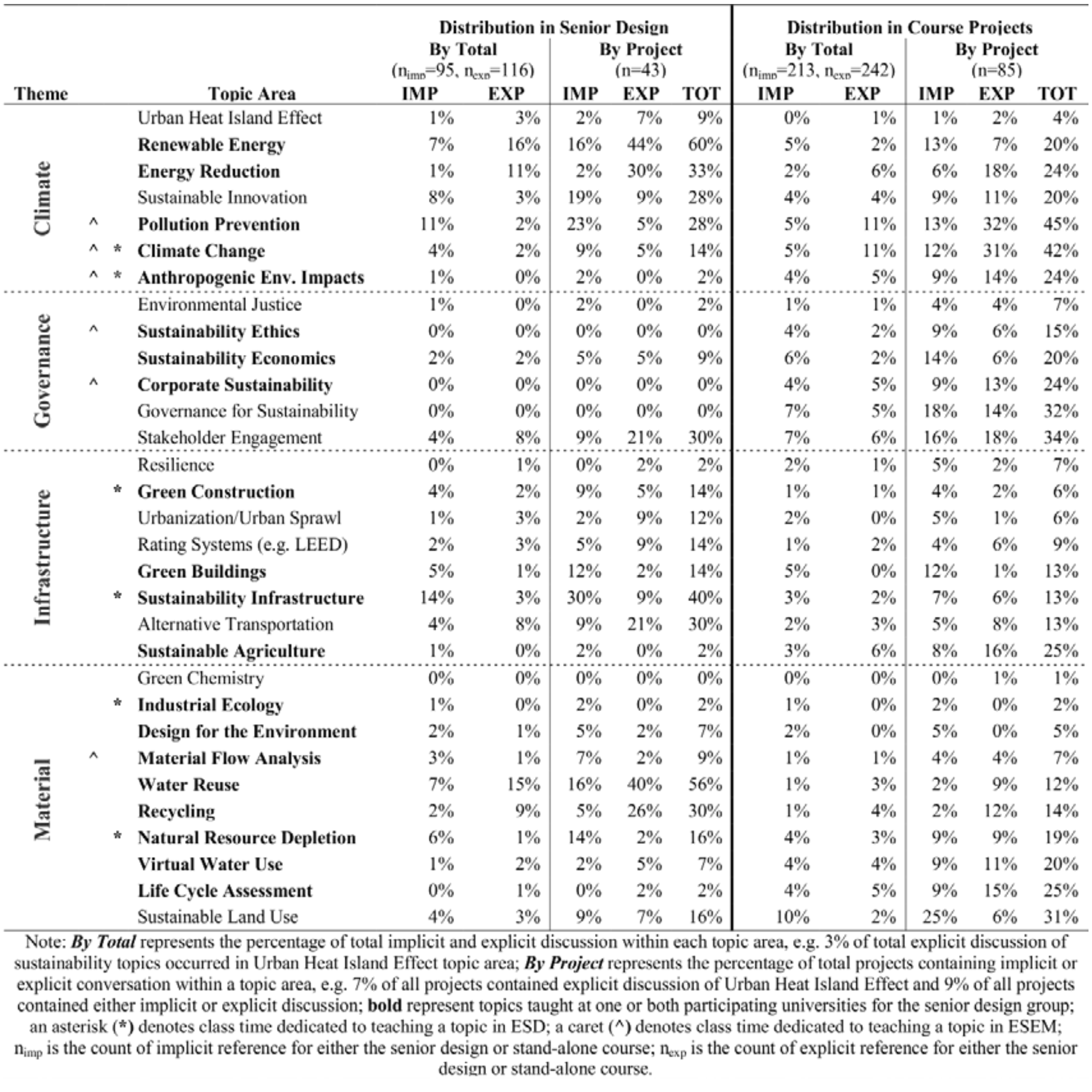
Distribution of *Sustainability Links* (McCormick, Lawyer et al. 2015) achieved by projects for the senior design and stand-alone sustainable engineering courses studied. Mann-Whitney U test results are included.



	Sustainability Linkage Achieved **(ordinal score)**								
Course Project Sample Group	No Linkage **1**	Concept **2**	Crosslink **3**	Inter-dependency **4**	Count	Rank Sum	U **(tested)**	*U-critical*	*p-value*
Senior Design Projects	7	70	23	0	100	15,199	13,652		
Stand-alone Course Projects	11	142	74	11	238	42,093	**10,149**		
								10,748	*0.012*

A.4 DISTRIBUTION OF DISCUSSION OF SUSTAINABILITY TOPICS

Distribution of implicit and explicit discussion within student projects for the senior design and stand-alone courses studied. Results are organized *By Total* (the portion of implicit or explicit references made in a topic from the total number of implicit or explicit references made within a project group) and *By Project* (the portion of implicit or explicit references made in a topic from the total number of projects in a project group).

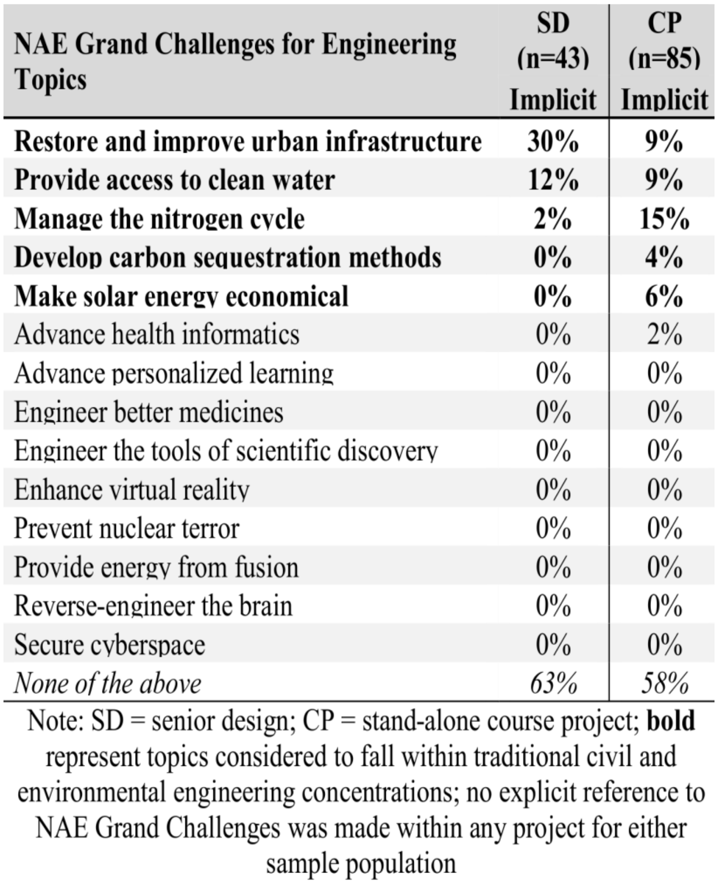


			Distribution in Senior Design					Distribution in Course Projects				
			By Total (n_{imp}=95, n_{exp}=116)		By Project (n=43)			By Total (n_{imp}=213, n_{exp}=242)		By Project (n=85)		
Theme		Topic Area	IMP	EXP	IMP	EXP	TOT	IMP	EXP	IMP	EXP	TOT
Climate		Urban Heat Island Effect	1%	3%	2%	7%	9%	0%	1%	1%	2%	4%
		Renewable Energy	7%	16%	16%	44%	60%	5%	2%	13%	7%	20%
		Energy Reduction	1%	11%	2%	30%	33%	2%	6%	6%	18%	24%
		Sustainable Innovation	8%	3%	19%	9%	28%	4%	4%	9%	11%	20%
	^	**Pollution Prevention**	11%	2%	23%	5%	28%	5%	11%	13%	32%	45%
	^ *	**Climate Change**	4%	2%	9%	5%	14%	5%	11%	12%	31%	42%
	^ *	**Anthropogenic Env. Impacts**	1%	0%	2%	0%	2%	4%	5%	9%	14%	24%
Governance		Environmental Justice	1%	0%	2%	0%	2%	1%	1%	4%	4%	7%
	^	**Sustainability Ethics**	0%	0%	0%	0%	0%	4%	2%	9%	6%	15%
		Sustainability Economics	2%	2%	5%	5%	9%	6%	2%	14%	6%	20%
	^	**Corporate Sustainability**	0%	0%	0%	0%	0%	4%	5%	9%	13%	24%
		Governance for Sustainability	0%	0%	0%	0%	0%	7%	5%	18%	14%	32%
		Stakeholder Engagement	4%	8%	9%	21%	30%	7%	6%	16%	18%	34%
Infrastructure		Resilience	0%	1%	0%	2%	2%	2%	1%	5%	2%	7%
	*	**Green Construction**	4%	2%	9%	5%	14%	1%	1%	4%	2%	6%
		Urbanization/Urban Sprawl	1%	3%	2%	9%	12%	2%	0%	5%	1%	6%
		Rating Systems (e.g. LEED)	2%	3%	5%	9%	14%	1%	2%	4%	6%	9%
		Green Buildings	5%	1%	12%	2%	14%	5%	0%	12%	1%	13%
	*	**Sustainability Infrastructure**	14%	3%	30%	9%	40%	3%	2%	7%	6%	13%
		Alternative Transportation	4%	8%	9%	21%	30%	2%	3%	5%	8%	13%
		Sustainable Agriculture	1%	0%	2%	0%	2%	3%	6%	8%	16%	25%
Material		Green Chemistry	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%
	*	**Industrial Ecology**	1%	0%	2%	0%	2%	1%	0%	2%	0%	2%
		Design for the Environment	2%	1%	5%	2%	7%	2%	0%	5%	0%	5%
	^	**Material Flow Analysis**	3%	1%	7%	2%	9%	1%	1%	4%	4%	7%
		Water Reuse	7%	15%	16%	40%	56%	1%	3%	2%	9%	12%
		Recycling	2%	9%	5%	26%	30%	1%	4%	2%	12%	14%
	*	**Natural Resource Depletion**	6%	1%	14%	2%	16%	4%	3%	9%	9%	19%
		Virtual Water Use	1%	2%	2%	5%	7%	4%	4%	9%	11%	20%
		Life Cycle Assessment	0%	1%	0%	2%	2%	4%	5%	9%	15%	25%
		Sustainable Land Use	4%	3%	9%	7%	16%	10%	2%	25%	6%	31%

Note: ***By Total*** represents the percentage of total implicit and explicit discussion within each topic area, e.g. 3% of total explicit discussion of sustainability topics occurred in Urban Heat Island Effect topic area; ***By Project*** represents the percentage of total projects containing implicit or explicit conversation within a topic area, e.g. 7% of all projects contained explicit discussion of Urban Heat Island Effect and 9% of all projects contained either implicit or explicit discussion; **bold** represent topics taught at one or both participating universities for the senior design group; an asterisk (*****) denotes class time dedicated to teaching a topic in ESD; a caret (**^**) denotes class time dedicated to teaching a topic in ESEM; n_{imp} is the count of implicit reference for either the senior design or stand-alone course; n_{exp} is the count of explicit reference for either the senior design or stand-alone course.

A.5 DISTRIBUTION OF REFERENCES TO NAE CHALLENGES

The distribution of implicit references to *NAE Grand Challenges*, including the category "none of the above" (no reference was made to NAE Grand Challenges) (NAE 2015).



NAE Grand Challenges for Engineering Topics	**SD (n=43)**	**CP (n=85)**
	Implicit	**Implicit**
Restore and improve urban infrastructure	**30%**	**9%**
Provide access to clean water	**12%**	**9%**
Manage the nitrogen cycle	**2%**	**15%**
Develop carbon sequestration methods	**0%**	**4%**
Make solar energy economical	**0%**	**6%**
Advance health informatics	0%	2%
Advance personalized learning	0%	0%
Engineer better medicines	0%	0%
Engineer the tools of scientific discovery	0%	0%
Enhance virtual reality	0%	0%
Prevent nuclear terror	0%	0%
Provide energy from fusion	0%	0%
Reverse-engineer the brain	0%	0%
Secure cyberspace	0%	0%
None of the above	*63%*	*58%*

Note: SD = senior design; CP = stand-alone course project; **bold** represent topics considered to fall within traditional civil and environmental engineering concentrations; no explicit reference to NAE Grand Challenges was made within any project for either sample population

APPENDIX B

SUPPORTING INFORMATION FOR A SURVEY OF HOMEOWNERS' MOTIVATIONS FOR THE ADOPTION OF ENERGY EFFICIENCY MEASURES: EVALUATING A HOLISTIC ENERGY ASSESSMENT PROGRAM

Homeowners were recommended five energy efficiency measures (EEM) for investment in their home. The tables presented in this section, include the list of measures recommended to homeowners, organized by the priority assigned by the student assessors. Homeowners' responses to survey questions asking (1) if they adopted the measure or not, and (2) their level of agreement with a positive statement regarding seven identified motivators, are included.

Note: EEM 1 through EEM 5 - the five prioritized energy efficiency measures recommended to homeowners through the informative energy assessment report; Adopt - homeowners' responses to their choose on adoption of an EEM, where: (1) Yes, I have done it, (2) I will do it in the next month, (3) I will do it in the next year, (4) I do not anticipate ever making this improvement, and (5) I am uncertain; SAVE - This recommendation will save me money on my utility bills, COMF - This recommendation will improve the comfort of my home, BUDG - The cost of performing this recommendation is within budget, TIME - I will have time to complete this recommendation, INFO - I have the information needed to perform this recommendation, SKIL - I have skills and/or abilities needed to perform this recommendation, PRIO - This recommendation is a priority on my list of home improvement projects, values in these columns represent homeowners responses strongly disagree (-2), disagree (-1), agree (1), and strongly agree (2); A - Upgraded light bulbs to compact fluorescent or LEDs, B - Upgraded any major appliance (e.g. refrigerator, clothes washer, clothes dryer), C - Added a home energy management system, D - Upgraded to smart power strips, E - Upgraded your primary heating source (e.g. furnace, boiler, heat pump), F - Upgraded programmable thermostat, G - Weatherized doors or windows, H - Added air duct insulation and/or air sealant, I - Upgraded central air conditioner, J - Added whole house fan, K - Added ductless air conditioner, L - Upgraded the water heater, M - Added water heater and/or pipe insulation, N - Installed water reducing technology (e.g. faucet aerators, low-flow fixtures), O - Repointed brick exterior, P - Added insulation in attic, walls, and/or floors, Q - Upgraded windows (e.g. storm windows, double pane), R - Purchased renewable energy from a utility, S - Added smoke detectors, T - Added carbon monoxide detectors, U - Installed on-site renewable energy (e.g. solar panels, solar lights, wind turbine, solar water heating); WH/WR - Water Heating and Water Reduction, Other - Other Improvements

B.1 HOMEOWNER RESPONSES TO EEM 1

	EEM 1									
H/O ID	EEMagg	EEMsub	Adopt	SAVE	COMF	BUDG	TIME	INFO	SKIL	PRIO
1	HVAC	H	3	1	1	1	2	-2	1	-1
2	Envelope	P	1	2	1	1	-1	-1	-1	1
5	Lighting	A	1	1	1	1	1	1	2	2
6	Lighting	A	1	2	2	2	2	2	2	2
9	Envelope	P	1	2	2	2	2	2	2	2
21	Envelope	O	3	1	2	-1	-1	2	2	2
24	Envelope	Q	1	1	2	2	1	1	1	1
25	Envelope	G	3	1	1	1	-1	1	1	2
26	HVAC	F	4	-1	-1	1	1	1	1	-1
28	Envelope	O	2	2	1	1	1	1	1	1
48	Other	C	4	-	-	-	-	-	-	-
51	Envelope	P	1	2	2	2	2	2	-1	2
60	Envelope	P	4	1	-1	1	-1	1	-1	-1
68	HVAC	H	3	2	1	2	1	-1	-1	-1
70	Envelope	O	3	2	1	-1	1	-1	-2	1
78	Lighting	A	1	2	1	1	1	2	2	-1
81	Other	S	3	1	1	-2	1	1	-2	1
82	WH/WR	M	2	1	-1	1	1	1	1	1
83	Envelope	P	1	2	2	2	2	2	-1	2
85	Envelope	P	1	1	1	1	1	1	-1	1
87	WH/WR	M	5	1	-1	-1	-1	1	1	1
88	Envelope	P	1	2	2	2	2	2	2	2
90	HVAC	E	5	2	2	1	1	1	-2	-1
91	HVAC	K	4	-2	1	-1	2	2	-2	-2
93	Lighting	A	3	1	-1	-1	-1	-1	1	1
98	Envelope	P	5	1	1	-1	-1	-1	-1	-1
106	Envelope	O	1	2	2	2	-1	1	1	1

B.2 HOMEOWNER RESPONSES TO EEM 2

	EEM 2									
H/O ID	EEMagg	EEMsub	Adopt	SAVE	COMF	BUDG	TIME	INFO	SKIL	PRIO
1	Appliances	B	1	2	-2	2	2	2	2	-2
2	Envelope	P	4	1	1	-1	1	-2	1	-1
5	HVAC	H	5	-	-	-	-	-	-	-
6	HVAC	F	1	2	2	1	2	2	2	1
9	Envelope	P	1	2	2	2	2	2	2	2
21	Lighting	A	1	1	-2	2	2	2	2	2
24	Envelope	O	4	-1	-1	2	-1	2	-1	-1
25	HVAC	E	5	1	1	-1	-1	1	-1	-1
26	Envelope	P	5	1	-1	-1	-1	-1	-2	-1
28	Other	C	4	-1	-1	1	1	1	1	-1
48	Envelope	O	4	-	-	-	-	-	-	-
51	Appliances	D	3	1	-1	1	-1	1	2	-1
60	Envelope	O	4	2	1	-1	-1	-1	-2	-1
68	Envelope	P	3	2	2	-1	-1	1	-1	2
70	Envelope	P	3	2	1	-1	1	-1	-2	1
78	Other	U	4	2	1	-2	-2	-1	-2	-2
81	WH/WR	L	3	1	1	-2	1	1	-2	1
82	HVAC	H	5	1	1	1	1	-1	-1	1
83	Lighting	A	1	1	1	2	2	2	2	2
85	Envelope	P	5	1	1	-1	-1	1	-1	-1
87	HVAC	E	3	1	1	1	1	1	-1	1
88	Envelope	P	1	2	2	2	2	2	2	2
90	HVAC	F	3	2	2	1	1	1	-2	1
91	Envelope	Q	3	1	2	1	2	2	1	2
93	Other	C	5	1	1	-	-1	-1	-1	-
98	Envelope	O	5	-1	1	-1	-1	-1	-1	-1
106	Envelope	P	5	2	2	-1	-1	-1	-1	2

B.3 HOMEOWNER RESPONSES TO EEM 3

	EEM 3									
H/O ID	EEMagg	EEMsub	Adopt	SAVE	COMF	BUDG	TIME	INFO	SKIL	PRIO
1	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-
5	HVAC	E	1	2	2	2	1	1	1	2
6	HVAC	H	3	2	2	1	1	2	1	1
9	Envelope	O	1	2	2	2	2	2	2	2
21	Envelope	P	3	1	-1	-1	1	1	1	1
24	Envelope	G	3	1	1	2	1	1	1	-1
25	HVAC	I	1	1	1	1	1	1	-1	2
26	Envelope	G	1	2	-1	2	2	2	1	1
28	Envelope	Q	3	1	1	-1	-1	1	1	-1
48	Lighting	A	1	-	-	-	-	-	-	-
51	WH/WR	M	4	-1	-1	-1	-1	-1	-1	-1
60	WH/WR	N	1	1	-1	1	1	1	1	1
68	HVAC	F	1	2	2	2	1	1	-1	2
70	Envelope	P	3	2	1	-1	1	-1	-2	1
78	HVAC	F	4	-1	-1	1	1	1	1	-2
81	HVAC	H	3	1	1	-2	1	1	-2	1
82	Other	T	1	-1	1	1	1	1	1	1
83	WH/WR	M	4	-1	-1	2	2	1	1	-1
85	Envelope	P	3	1	1	-1	-1	1	1	-1
87	Envelope	Q	1	2	2	2	2	2	2	2
88	Appliances	D	4	-1	-2	2	2	2	2	2
90	Envelope	Q	1	2	2	2	2	2	-2	1
91	Other	C	4	1	-1	-1	1	1	1	-2
93	Envelope	P	1	1	1	-1	1	1	-1	-1
98	HVAC	F	4	-1	-1	-2	-2	-2	-2	-2
106	Envelope	P	4	-	-	-	-	-	-	-

B.4 HOMEOWNER RESPONSES TO EEM 4

H/O ID	EEM 4									
	EEMagg	EEMsub	Adopt	SAVE	COMF	BUDG	TIME	INFO	SKIL	PRIO
1	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-
5	Appliances	B	1	-	-	-	-	-	-	-
6	HVAC	H	3	2	2	-1	1	2	-1	1
9	Appliances	B	3	2	2	1	-1	-1	-1	1
21	Envelope	G	4	-1	-2	-1	-1	-1	-1	-1
24	HVAC	H	3	-1	1	1	1	1	1	-1
25	WH/WR	M	3	1	1	2	1	1	2	1
26	WH/WR	M	1	1	-1	2	2	1	1	1
28	WH/WR	M	3	1	-1	1	1	1	1	1
48	Envelope	P	5	-	-	-	-	-	-	-
51	Envelope	G	1	1	2	2	2	1	1	2
60	WH/WR	L	4	1	-1	-1	-1	1	-2	-1
68	WH/WR	M	5	1	1	1	-1	-1	-1	1
70	Envelope	Q	4	1	1	-1	1	1	-2	-1
78	Appliances	D	1	1	1	1	1	1	1	1
81	Other	R	2	1	1	-1	1	-1	-2	1
82	Envelope	G	3	1	1	1	1	1	1	1
83	Envelope	G	2	1	-1	2	1	1	1	-1
85	WH/WR	M	3	1	-1	1	1	1	-1	-1
87	Envelope	G	1	2	2	2	2	2	2	2
88	Envelope	G	1	2	2	2	2	2	2	2
90	Envelope	G	3	2	2	2	1	1	-2	-1
91	WH/WR	M	5	1	-1	2	2	2	2	-2
93	HVAC	E	1	1	1	-1	1	1	-1	1
98	Appliances	D	5	-1	-1	-1	-1	-1	-1	-1
106	Envelope	Q	3	1	2	-1	-1	-1	-1	2

B.5 HOMEOWNER RESPONSES TO EEM 5

H/O ID	EEM 5									
	EEMagg	EEMsub	Adopt	SAVE	COMF	BUDG	TIME	INFO	SKIL	PRIO
1	-	-	-	-	-	-	-	-	-	-
2	-	-	-	-	-	-	-	-	-	-
5	Appliances	B	5	-	-	-	-	-	-	-
6	HVAC	E	5	2	2	-2	1	2	-2	-1
9	WH/WR	L	3	2	2	2	2	2	2	2
21	Appliances	D	4	2	-2	2	2	2	2	-2
24	Appliances	B	1	2	-1	1	1	1	2	2
25	Envelope	P	3	1	1	1	-1	-1	-1	1
26	Appliances	D	5	-1	-1	-1	1	-1	1	-1
28	Appliances	B	3	1	1	1	1	1	1	1
48	HVAC	J	4	-	-	-	-	-	-	-
51	-	-	-	-	-	-	-	-	-	-
60	WH/WR	M	4	1	-1	-1	-1	1	-2	-1
68	Appliances	D	5	1	-1	2	1	-2	1	-2
70	Appliances	B	3	1	-1	-1	1	-1	-1	-1
78	Other	R	1	-2	-2	1	1	1	1	1
81	Envelope	P	3	1	1	-2	1	1	-2	1
82	Other	C	5	1	1	-1	1	-1	1	-1
83	Envelope	O	1	1	2	2	2	2	-2	2
85	Envelope	O	5	1	1	-1	-1	-1	-1	-1
87	Envelope	P	4	1	1	-1	-1	-1	-1	-1
88	WH/WR	M	3	1	1	1	1	1	1	-1
90	WH/WR	M	5	-1	-1	-1	-1	-1	-1	-1
91	Envelope	G	1	1	2	2	2	2	2	2
93	WH/WR	M	5	1	-	-	-	-	-	-
98	Envelope	P	4	-2	-2	-2	-2	-2	-2	-2
106	Appliances	D	3	-	-	-	-	-	-	-

APPENDIX C

SUPPORTING INFORMATION FOR SYNERGIZING DISPARATE COMPONENT-LEVEL ENERGY RESOURCES INTO A SINGLE WHOLE BUILDING PACKAGE TO SUPPORT ENERGY CONSERVATION ACTION IN SMALL COMMERCIAL BUILDINGS

Presented below is supporting information for the development and demonstration of the Building Energy Assessment Resource (BEAR). First is a summary list of the energy estimate resources identified and incorporated to BEAR, including the type of resource, e.g. calculator, database or benchmark, and if it is located within BEAR (internal) or as an external link. Next, screen captures of BEAR provide demonstrative illustrations including example data from actual tenants. Lastly, a complete list of data collected during the use of BEAR is included as part of supplemental information to the data analysis of BEARs performance.

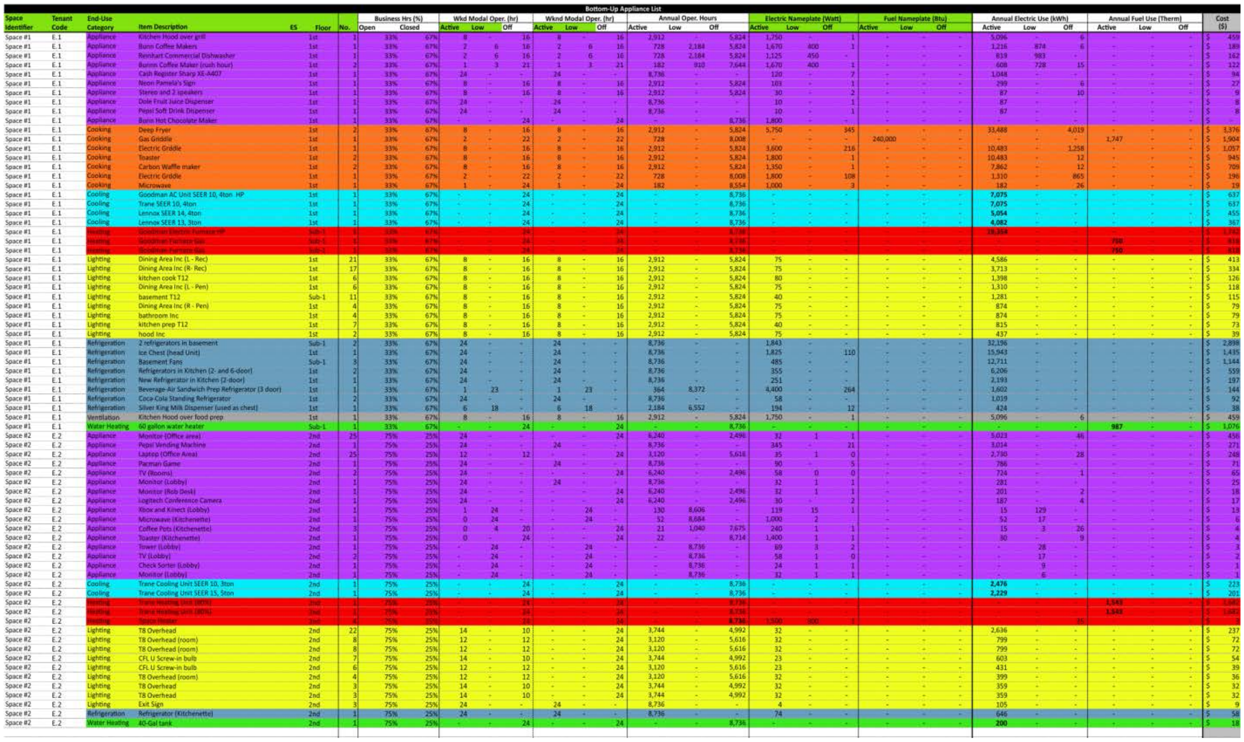
C.1 LIST OF ENERGY ESTIMATE RESOURCES

Below is a complete list of energy estimate resources assembled in BEAR. Note: ES is EnergyStar; DOE is U.S. Department of Energy; CEC is California Energy Commission; NREL is National Renewable Energy Laboratory; Under Source, 1 is (Energy Star 2016), 2 is (U.S. DOE 2014), 3 is (Berkeley Lab 2014), 4 is (PNNL 2016), 5 is (CEC 2017), 6 is (Energy Star 2016) and 7 is (http://pvwatts.nrel.gov/)

General Area	**Specific Target System of Energy Tool/Database**	**Source**	
Space Heating & Cooling	Air-Cooled Chillers	DOE	[2]
	Boilers	DOE	[2]
	Commercial Heat Pumps (HP)	DOE	[2]
	Commercial Rooftop Air Conditioners (AC)	DOE	[2, 4]
	Air-Source HP	ES & DOE	[1, 2]
	Central AC	ES & DOE	[1, 2]
	Gas Furnace	ES & DOE	[1, 2]
	Ceiling Fan	ES	[1]
Plug Load (Appliance & Equipment)	Office Equipment	ES & DOE	[1, 2]
	Dishwasher	ES & DOE	[1, 2]
	Clothes Washer	DOE	[2]
	Fryers	ES & DOE	[1, 2]
	Griddles	ES & DOE	[1, 2]
	Hot Food Holding Cabinets	ES & DOE	[1, 2]
	Ovens	ES & DOE	[1, 2]
	Ice Machines	ES & DOE	[1, 2]
	Commercial Refrigerators	ES	[1]
	Steam Cookers	DOE	[2]
	Standby Power Table (measured loads)	DOE	[3]
	CEC Appliance Search (known wattages)	CEC	[5]
	Certified Product Database (varying information)	ES	[6]
	Light Bulbs	ES & DOE	[1, 2]
	Lighting Ballasts	ES	[1]
Renewable & Passive Energy Sources	Solar Hot Water System	DOE	[2]
	Solar PV Array	NREL	[7]
	Cool Roof	DOE	[2]
Water Heating & Water Use	Electric & Gas Water Heaters	DOE	[2]
	Faucets, showerheads & Urinals	DOE	[2]

C.2 BEAR'S SYSTEM INVENTORY

Presented is a screen capture of BEAR's inventory data entry form. Data collected through the Energy Audit Walkthrough (Step 2) is entered in this page during Step 3. Note: green column headings indicate fields requesting data entry, including modal power, modal operation, and notes. The information entered in this example is that of Building E, tenants E.1 and E.2.

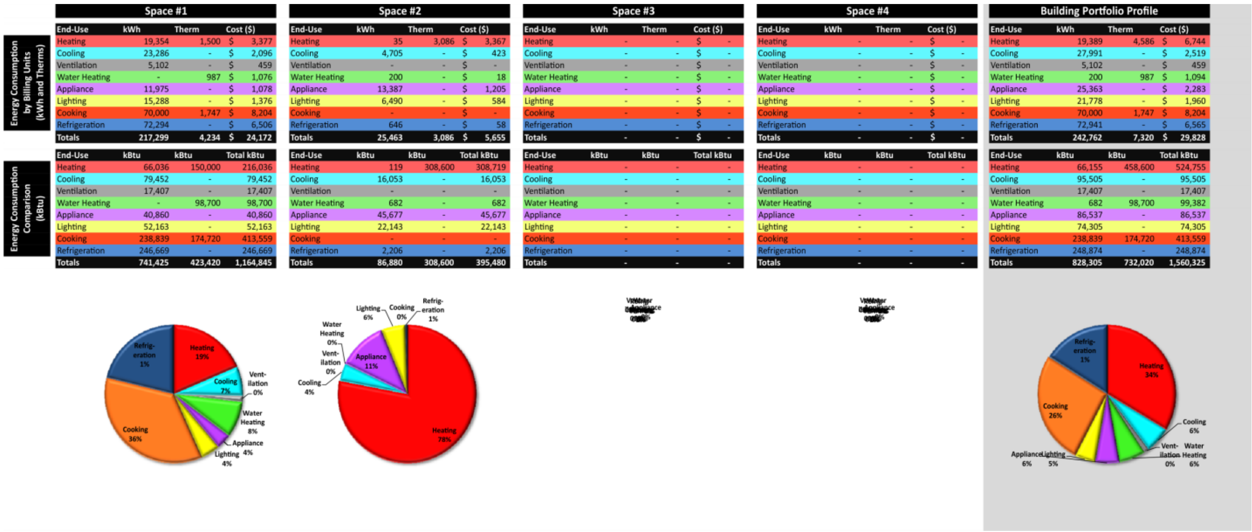


Bottom-Up Appliance List

Space Identifier	Tenant Code	End-Use Category	Item Description	ES	Floor	No.	Business Hrs (%)		Wkd Modal Oper. (hr)			Wknd Modal Oper. (hr)			Annual Oper. Hours			Electric Nameplate (Watt)			Fuel Nameplate (Btu)			Annual Electric Use (kWh)			Annual Fuel Use (Therm)			Cost ($)
							Open	Closed	Active	Low	Off	Active	Low	Off	Active	Low	Off	Active	Low	Off	Active	Low	Off	Active	Low	Off	Active	Low	Off	
Space #1	E.1	Appliance	Kitchen Hood over grill		1st	1	33%	67%	8	-	16	8	-	16	2,912	-	5,824	1,750	-	1	-	-	-	5,096	-	6	-	-	-	$ 459
Space #1	E.1	Appliance	Bunn Coffee Makers		1st	1	33%	67%	2	6	16	2	6	16	728	2,184	5,824	1,670	400	1	-	-	-	1,216	874	6	-	-	-	$ 189
Space #1	E.1	Appliance	Reinhart Commercial Dishwasher		1st	1	33%	67%	2	6	16	2	6	16	728	2,184	5,824	1,125	450	-	-	-	-	819	983	-	-	-	-	$ 162
Space #1	E.1	Appliance	Bunnn Coffee Maker (rush hour)		1st	2	33%	67%	1	3	21	1	3	21	182	910	7,644	1,670	400	1	-	-	-	608	728	15	-	-	-	$ 122
Space #1	E.1	Appliance	Cash Register Sharp XE-A407		1st	1	33%	67%	24	-	-	24	-	-	8,736	-	-	120	-	7	-	-	-	1,048	-	-	-	-	-	$ 94
Space #1	E.1	Appliance	Neon Pamela's Sign		1st	1	33%	67%	8	-	16	8	-	16	2,912	-	5,824	103	-	1	-	-	-	299	-	6	-	-	-	$ 27
Space #1	E.1	Appliance	Stereo and 2 speakers		1st	1	33%	67%	8	-	16	8	-	16	2,912	-	5,824	30	-	2	-	-	-	87	-	10	-	-	-	$ 9
Space #1	E.1	Appliance	Dole Fruit Juice Dispenser		1st	1	33%	67%	24	-	-	24	-	-	8,736	-	-	10	-	1	-	-	-	87	-	-	-	-	-	$ 8
Space #1	E.1	Appliance	Pepsi Soft Drink Dispenser		1st	1	33%	67%	24	-	-	24	-	-	8,736	-	-	10	-	1	-	-	-	87	-	-	-	-	-	$ 8
Space #1	E.1	Appliance	Bunn Hot Chocolate Maker		1st	1	33%	67%	-	-	24	-	-	24	-	-	8,736	1,800	-	-	-	-	-	-	-	-	-	-	-	$ -
Space #1	E.1	Cooking	Deep Fryer		1st	2	33%	67%	8	-	16	8	-	16	2,912	-	5,824	5,750	-	345	-	-	-	33,488	-	4,019	-	-	-	$ 3,376
Space #1	E.1	Cooking	Gas Griddle		1st	1	33%	67%	2	-	22	2	-	22	728	-	8,008	-	-	-	240,000	-	-	-	-	-	1,747	-	-	$ 1,904
Space #1	E.1	Cooking	Electric Griddle		1st	1	33%	67%	8	-	16	8	-	16	2,912	-	5,824	3,600	-	216	-	-	-	10,483	-	1,258	-	-	-	$ 1,057
Space #1	E.1	Cooking	Toaster		1st	2	33%	67%	8	-	16	8	-	16	2,912	-	5,824	1,800	-	1	-	-	-	10,483	-	12	-	-	-	$ 945
Space #1	E.1	Cooking	Carbon Waffle maker		1st	2	33%	67%	8	-	16	8	-	16	2,912	-	5,824	1,350	-	1	-	-	-	7,862	-	12	-	-	-	$ 709
Space #1	E.1	Cooking	Electric Griddle		1st	1	33%	67%	2	-	22	2	-	22	728	-	8,008	1,800	-	108	-	-	-	1,310	-	865	-	-	-	$ 196
Space #1	E.1	Cooking	Microwave		1st	1	33%	67%	1	-	24	1	-	24	182	-	8,554	1,000	-	3	-	-	-	182	-	26	-	-	-	$ 19
Space #1	E.1	Cooling	Goodman AC Unit SEER 10, 4ton HP		1st	1	33%	67%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	**7,075**	-	-	-	-	-	$ 637
Space #1	E.1	Cooling	Trane SEER 10, 4ton		1st	1	33%	67%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	**7,075**	-	-	-	-	-	$ 637
Space #1	E.1	Cooling	Lennox SEER 14, 4ton		1st	1	33%	67%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	**5,054**	-	-	-	-	-	$ 455
Space #1	E.1	Cooling	Lennox SEER 13, 3ton		1st	1	33%	67%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	**4,082**	-	-	-	-	-	$ 367
Space #1	E.1	Heating	Goodman Electric Furnace HP		Sub-1	1	33%	67%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	**19,354**	-	-	-	-	-	$ 1,742
Space #1	E.1	Heating	Goodman Furnace Gas		Sub-1	1	33%	67%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	-	-	-	**750**	-	-	$ 818
Space #1	E.1	Heating	Goodman Furnace Gas		Sub-1	1	33%	67%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	-	-	-	**750**	-	-	$ 818
Space #1	E.1	Lighting	Dining Area Inc (L - Rec)		1st	21	33%	67%	8	-	16	8	-	16	2,912	-	5,824	75	-	-	-	-	-	4,586	-	-	-	-	-	$ 413
Space #1	E.1	Lighting	Dining Area Inc (R- Rec)		1st	17	33%	67%	8	-	16	8	-	16	2,912	-	5,824	75	-	-	-	-	-	3,713	-	-	-	-	-	$ 334
Space #1	E.1	Lighting	kitchen cook T12		1st	6	33%	67%	8	-	16	8	-	16	2,912	-	5,824	80	-	-	-	-	-	1,398	-	-	-	-	-	$ 126
Space #1	E.1	Lighting	Dining Area Inc (L - Pen)		1st	6	33%	67%	8	-	16	8	-	16	2,912	-	5,824	75	-	-	-	-	-	1,310	-	-	-	-	-	$ 118
Space #1	E.1	Lighting	basement T12		Sub-1	11	33%	67%	8	-	16	8	-	16	2,912	-	5,824	40	-	-	-	-	-	1,281	-	-	-	-	-	$ 115
Space #1	E.1	Lighting	Dining Area Inc (R - Pen)		1st	4	33%	67%	8	-	16	8	-	16	2,912	-	5,824	75	-	-	-	-	-	874	-	-	-	-	-	$ 79
Space #1	E.1	Lighting	bathroom Inc		1st	4	33%	67%	8	-	16	8	-	16	2,912	-	5,824	75	-	-	-	-	-	874	-	-	-	-	-	$ 79
Space #1	E.1	Lighting	kitchen prep T12		1st	7	33%	67%	8	-	16	8	-	16	2,912	-	5,824	40	-	-	-	-	-	815	-	-	-	-	-	$ 73
Space #1	E.1	Lighting	hood Inc		1st	2	33%	67%	8	-	16	8	-	16	2,912	-	5,824	75	-	-	-	-	-	437	-	-	-	-	-	$ 39
Space #1	E.1	Refrigeration	2 refrigerators in basement		Sub-1	2	33%	67%	24	-	-	24	-	-	8,736	-	-	1,843	-	-	-	-	-	32,196	-	-	-	-	-	$ 2,898
Space #1	E.1	Refrigeration	Ice Chest (head Unit)		1st	1	33%	67%	24	-	-	24	-	-	8,736	-	-	1,825	-	110	-	-	-	15,943	-	-	-	-	-	$ 1,435
Space #1	E.1	Refrigeration	Basement Fans		Sub-1	3	33%	67%	24	-	-	24	-	-	8,736	-	-	485	-	-	-	-	-	12,711	-	-	-	-	-	$ 1,144
Space #1	E.1	Refrigeration	Refrigerators in Kitchen (2- and 6-door)		1st	2	33%	67%	24	-	-	24	-	-	8,736	-	-	355	-	-	-	-	-	6,206	-	-	-	-	-	$ 559
Space #1	E.1	Refrigeration	New Refrigerator in Kitchen (2-door)		1st	1	33%	67%	24	-	-	24	-	-	8,736	-	-	251	-	-	-	-	-	2,193	-	-	-	-	-	$ 197
Space #1	E.1	Refrigeration	Beverage-Air Sandwich Prep Refrigerator (3 door)		1st	1	33%	67%	1	23	-	1	23	-	364	8,372	-	4,400	-	264	-	-	-	1,602	-	-	-	-	-	$ 144
Space #1	E.1	Refrigeration	Coca-Cola Standing Refrigerator		1st	2	33%	67%	24	-	-	24	-	-	8,736	-	-	58	-	-	-	-	-	1,019	-	-	-	-	-	$ 92
Space #1	E.1	Refrigeration	Silver King Milk Dispenser (used as chest)		1st	1	33%	67%	6	18	-	6	18	-	2,184	6,552	-	194	-	12	-	-	-	424	-	-	-	-	-	$ 38
Space #1	E.1	Ventilation	Kitchen Hood over food prep		1st	1	33%	67%	8	-	16	8	-	16	2,912	-	5,824	1,750	-	1	-	-	-	5,096	-	6	-	-	-	$ 459
Space #1	E.1	Water Heating	60 gallon water heater		Sub-1	1	33%	67%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	-	-	-	**987**	-	-	$ 1,076
Space #2	E.2	Appliance	Monitor (Office area)		2nd	25	75%	25%	24	-	-	-	-	24	6,240	-	2,496	32	1	1	-	-	-	5,023	-	46	-	-	-	$ 456
Space #2	E.2	Appliance	Pepsi Vending Machine		2nd	1	75%	25%	24	-	-	24	-	-	8,736	-	-	345	-	21	-	-	-	3,014	-	-	-	-	-	$ 271
Space #2	E.2	Appliance	Laptop (Office Area)		2nd	25	75%	25%	12	-	12	-	-	24	3,120	-	5,616	35	1	0	-	-	-	2,730	-	28	-	-	-	$ 248
Space #2	E.2	Appliance	Pacman Game		2nd	1	75%	25%	24	-	-	24	-	-	8,736	-	-	90	-	5	-	-	-	786	-	-	-	-	-	$ 71
Space #2	E.2	Appliance	TV (Rooms)		2nd	2	75%	25%	24	-	-	-	-	24	6,240	-	2,496	58	0	0	-	-	-	724	-	1	-	-	-	$ 65
Space #2	E.2	Appliance	Monitor (Lobby)		2nd	1	75%	25%	24	-	-	24	-	-	8,736	-	-	32	1	1	-	-	-	281	-	-	-	-	-	$ 25
Space #2	E.2	Appliance	Monitor (Rob Desk)		2nd	1	75%	25%	24	-	-	-	-	24	6,240	-	2,496	32	1	1	-	-	-	201	-	2	-	-	-	$ 18
Space #2	E.2	Appliance	Logitech Conference Camera		2nd	1	75%	25%	24	-	-	-	-	24	6,240	-	2,496	30	-	2	-	-	-	187	-	4	-	-	-	$ 17
Space #2	E.2	Appliance	Xbox and Kinect (Lobby)		2nd	1	75%	25%	1	24	-	-	24	-	130	8,606	-	119	15	1	-	-	-	15	129	-	-	-	-	$ 13
Space #2	E.2	Appliance	Microwave (Kitchenette)		2nd	1	75%	25%	0	24	-	-	24	-	52	8,684	-	1,000	2		-	-	-	52	17	-	-	-	-	$ 6
Space #2	E.2	Appliance	Coffee Pots (Kitchenette)		2nd	3	75%	25%	0	4	20	-	-	24	21	1,040	7,675	240	1	1	-	-	-	15	3	26	-	-	-	$ 4
Space #2	E.2	Appliance	Toaster (Kitchenette)		2nd	1	75%	25%	0	-	24	-	-	24	22	-	8,714	1,400	1	1	-	-	-	30	-	9	-	-	-	$ 4
Space #2	E.2	Appliance	Tower (Lobby)		2nd	1	75%	25%	-	24	-	-	24	-	-	8,736	-	69	3	2	-	-	-	-	28	-	-	-	-	$ 3
Space #2	E.2	Appliance	TV (Lobby)		2nd	2	75%	25%	-	24	-	-	24	-	-	8,736	-	58	1	0	-	-	-	-	17	-	-	-	-	$ 2
Space #2	E.2	Appliance	Check Sorter (Lobby)		2nd	1	75%	25%	-	24	-	-	24	-	-	8,736	-	24	1	1	-	-	-	-	9	-	-	-	-	$ 1
Space #2	E.2	Appliance	Monitor (Lobby)		2nd	1	75%	25%	-	24	-	-	24	-	-	8,736	-	32	1	1	-	-	-	-	6	-	-	-	-	$ 1
Space #2	E.2	Cooling	Trane Cooling Unit SEER 10, 3ton		2nd	1	75%	25%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	**2,476**	-	-	-	-	-	$ 223
Space #2	E.2	Cooling	Trane Cooling Unit SEER 15, 5ton		2nd	1	75%	25%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	**2,229**	-	-	-	-	-	$ 201
Space #2	E.2	Heating	Trane Heating Unit (80%)		2nd	1	75%	25%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	-	-	-	**1,543**	-	-	$ 1,682
Space #2	E.2	Heating	Trane Heating Unit (80%)		2nd	1	75%	25%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	-	-	-	**1,543**	-	-	$ 1,682
Space #2	E.2	Heating	Space Heater		2nd	4	75%	25%	-	-	24	-	-	24	-	-	8,736	1,500	800	1	-	-	-	-	-	35	-	-	-	$ 3
Space #2	E.2	Lighting	T8 Overhead		2nd	22	75%	25%	14	-	10	-	-	24	3,744	-	4,992	32	-	-	-	-	-	2,636	-	-	-	-	-	$ 237
Space #2	E.2	Lighting	T8 Overhead (room)		2nd	8	75%	25%	12	-	12	-	-	24	3,120	-	5,616	32	-	-	-	-	-	799	-	-	-	-	-	$ 72
Space #2	E.2	Lighting	T8 Overhead (room)		2nd	8	75%	25%	12	-	12	-	-	24	3,120	-	5,616	32	-	-	-	-	-	799	-	-	-	-	-	$ 72
Space #2	E.2	Lighting	CFL U Screw-in bulb		2nd	7	75%	25%	14	-	10	-	-	24	3,744	-	4,992	23	-	-	-	-	-	603	-	-	-	-	-	$ 54
Space #2	E.2	Lighting	CFL U Screw-in bulb		2nd	6	75%	25%	12	-	12	-	-	24	3,120	-	5,616	23	-	-	-	-	-	431	-	-	-	-	-	$ 39
Space #2	E.2	Lighting	T8 Overhead (room)		2nd	4	75%	25%	12	-	12	-	-	24	3,120	-	5,616	32	-	-	-	-	-	399	-	-	-	-	-	$ 36
Space #2	E.2	Lighting	T8 Overhead		2nd	3	75%	25%	14	-	10	-	-	24	3,744	-	4,992	32	-	-	-	-	-	359	-	-	-	-	-	$ 32
Space #2	E.2	Lighting	T8 Overhead		2nd	3	75%	25%	14	-	10	-	-	24	3,744	-	4,992	32	-	-	-	-	-	359	-	-	-	-	-	$ 32
Space #2	E.2	Lighting	Exit Sign		2nd	3	75%	25%	24	-	-	24	-	-	8,736	-	-	4	-	-	-	-	-	105	-	-	-	-	-	$ 9
Space #2	E.2	Refrigeration	Refrigerator (Kitchenette)		2nd	1	75%	25%	24	-	-	24	-	-	8,736	-	-	74	-	-	-	-	-	646	-	-	-	-	-	$ 58
Space #2	E.2	Water Heating	40-Gal tank		2nd	1	75%	25%	-	-	24	-	-	24	-	-	8,736	-	-	-	-	-	-	**200**	-	-	-	-	-	$ 18

C.3 BEAR'S MIDPOINT ESTIMATE

Presented is a screen capture of the midpoint estimate page outlining the summation of energy consumed per end-use per space, and for all entered spaces, labeled "Building Portfolio Profile." Note: The information entered in this example is that of Building E, tenants E.1 and E.2.



Energy Consumption by Billing Units (kWh and Therms)

Space #1

End-Use	kWh	Therm	Cost ($)
Heating	19,354	1,500	$ 3,377
Cooling	23,286	-	$ 2,096
Ventilation	5,102	-	$ 459
Water Heating	-	987	$ 1,076
Appliance	11,975	-	$ 1,078
Lighting	15,288	-	$ 1,376
Cooking	70,000	1,747	$ 8,204
Refrigeration	72,294	-	$ 6,506
Totals	217,299	4,234	$ 24,172

Space #2

End-Use	kWh	Therm	Cost ($)
Heating	35	3,086	$ 3,367
Cooling	4,705	-	$ 423
Ventilation	-	-	$ -
Water Heating	200	-	$ 18
Appliance	13,387	-	$ 1,205
Lighting	6,490	-	$ 584
Cooking	-	-	$ -
Refrigeration	646	-	$ 58
Totals	25,463	3,086	$ 5,655

Space #3

End-Use	kWh	Therm	Cost ($)
Heating	-	-	$ -
Cooling	-	-	$ -
Ventilation	-	-	$ -
Water Heating	-	-	$ -
Appliance	-	-	$ -
Lighting	-	-	$ -
Cooking	-	-	$ -
Refrigeration	-	-	$ -
Totals	-	-	$ -

Space #4

End-Use	kWh	Therm	Cost ($)
Heating	-	-	$ -
Cooling	-	-	$ -
Ventilation	-	-	$ -
Water Heating	-	-	$ -
Appliance	-	-	$ -
Lighting	-	-	$ -
Cooking	-	-	$ -
Refrigeration	-	-	$ -
Totals	-	-	$ -

Building Portfolio Profile

End-Use	kWh	Therm	Cost ($)
Heating	19,389	4,586	$ 6,744
Cooling	27,991	-	$ 2,519
Ventilation	5,102	-	$ 459
Water Heating	200	987	$ 1,094
Appliance	25,363	-	$ 2,283
Lighting	21,778	-	$ 1,960
Cooking	70,000	1,747	$ 8,204
Refrigeration	72,941	-	$ 6,565
Totals	242,762	7,320	$ 29,828

Energy Consumption Comparison (kBtu)

Space #1

End-Use	kBtu	kBtu	Total kBtu
Heating	66,036	150,000	216,036
Cooling	79,452	-	79,452
Ventilation	17,407	-	17,407
Water Heating	-	98,700	98,700
Appliance	40,860	-	40,860
Lighting	52,163	-	52,163
Cooking	238,839	174,720	413,559
Refrigeration	246,669	-	246,669
Totals	741,425	423,420	1,164,845

Space #2

End-Use	kBtu	kBtu	Total kBtu
Heating	119	308,600	308,719
Cooling	16,053	-	16,053
Ventilation	-	-	-
Water Heating	682	-	682
Appliance	45,677	-	45,677
Lighting	22,143	-	22,143
Cooking	-	-	-
Refrigeration	2,206	-	2,206
Totals	86,880	308,600	395,480

Space #3

End-Use	kBtu	kBtu	Total kBtu
Heating	-	-	-
Cooling	-	-	-
Ventilation	-	-	-
Water Heating	-	-	-
Appliance	-	-	-
Lighting	-	-	-
Cooking	-	-	-
Refrigeration	-	-	-
Totals	-	-	-

Space #4

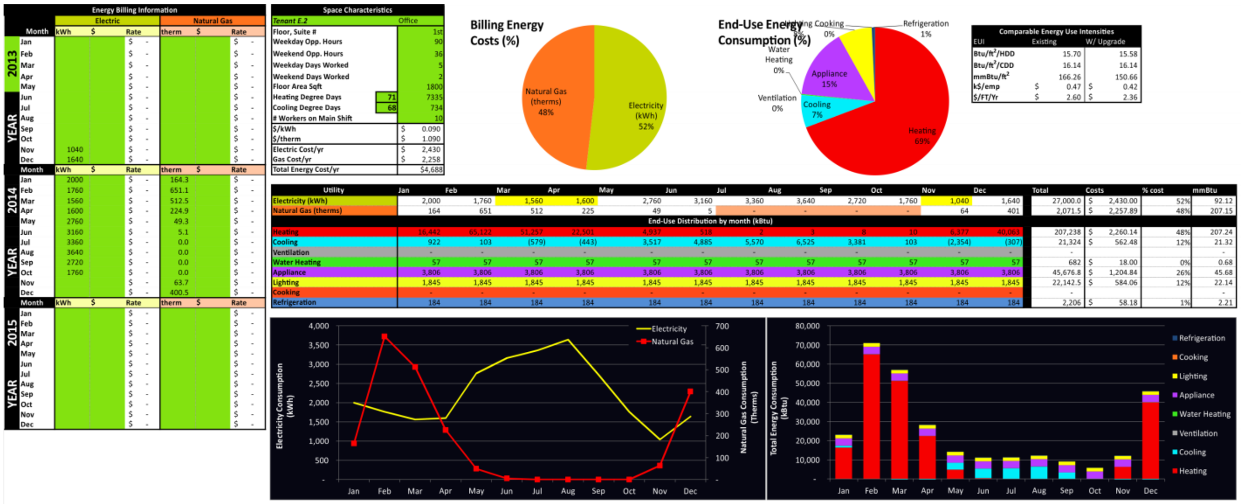
End-Use	kBtu	kBtu	Total kBtu
Heating	-	-	-
Cooling	-	-	-
Ventilation	-	-	-
Water Heating	-	-	-
Appliance	-	-	-
Lighting	-	-	-
Cooking	-	-	-
Refrigeration	-	-	-
Totals	-	-	-

Building Portfolio Profile

End-Use	kBtu	kBtu	Total kBtu
Heating	66,155	458,600	524,755
Cooling	95,505	-	95,505
Ventilation	17,407	-	17,407
Water Heating	682	98,700	99,382
Appliance	86,537	-	86,537
Lighting	74,305	-	74,305
Cooking	238,839	174,720	413,559
Refrigeration	248,874	-	248,874
Totals	828,305	732,020	1,560,325

C.4 BEAR'S BUILDING INFORMATION INTERFACE (OFFICE)

Presented is a screen capture of the building information interface, where business operational information, employee headcount, floor area, energy bills, and energy costs are entered. Note: the line graph illustrates energy billing information for electricity (kWh) and natural gas (therms), while the bar graph depicts the reconciled energy profile (step 5) for the building space; green cells indicate fields requesting data entry, including business operational information and energy bills. The information entered in this example is that of Building E, tenant E.2, an office.



Energy Billing Information

		Electric			Natural Gas		
	Month	kWh	$	Rate	therm	$	Rate
2013 YEAR	Jan			$ -			$ -
	Feb			$ -			$ -
	Mar			$ -			$ -
	Apr			$ -			$ -
	May			$ -			$ -
	Jun			$ -			$ -
	Jul			$ -			$ -
	Aug			$ -			$ -
	Sep			$ -			$ -
	Oct			$ -			$ -
	Nov	1040		$ -			$ -
	Dec	1640		$ -			$ -
	Month	kWh	$	Rate	therm	$	Rate
2014 YEAR	Jan	2000		$ -	164.3		$ -
	Feb	1760		$ -	651.1		$ -
	Mar	1560		$ -	512.5		$ -
	Apr	1600		$ -	224.9		$ -
	May	2760		$ -	49.3		$ -
	Jun	3160		$ -	5.1		$ -
	Jul	3360		$ -	0.0		$ -
	Aug	3640		$ -	0.0		$ -
	Sep	2720		$ -	0.0		$ -
	Oct	1760		$ -	0.0		$ -
	Nov			$ -	63.7		$ -
	Dec			$ -	400.5		$ -
	Month	kWh	$	Rate	therm	$	Rate
2015 YEAR	Jan			$ -			$ -
	Feb			$ -			$ -
	Mar			$ -			$ -
	Apr			$ -			$ -
	May			$ -			$ -
	Jun			$ -			$ -
	Jul			$ -			$ -
	Aug			$ -			$ -
	Sep			$ -			$ -
	Oct			$ -			$ -
	Nov			$ -			$ -
	Dec			$ -			$ -

Space Characteristics

Tenant E.2		Office
Floor, Suite #		1st
Weekday Opp. Hours		90
Weekend Opp. Hours		36
Weekday Days Worked		5
Weekend Days Worked		2
Floor Area Sqft		1800
Heating Degree Days	71	7335
Cooling Degree Days	68	734
# Workers on Main Shift		10
$/kWh		$ 0.090
$/therm		$ 1.090
Electric Cost/yr		$ 2,430
Gas Cost/yr		$ 2,258
Total Energy Cost/yr		$4,688

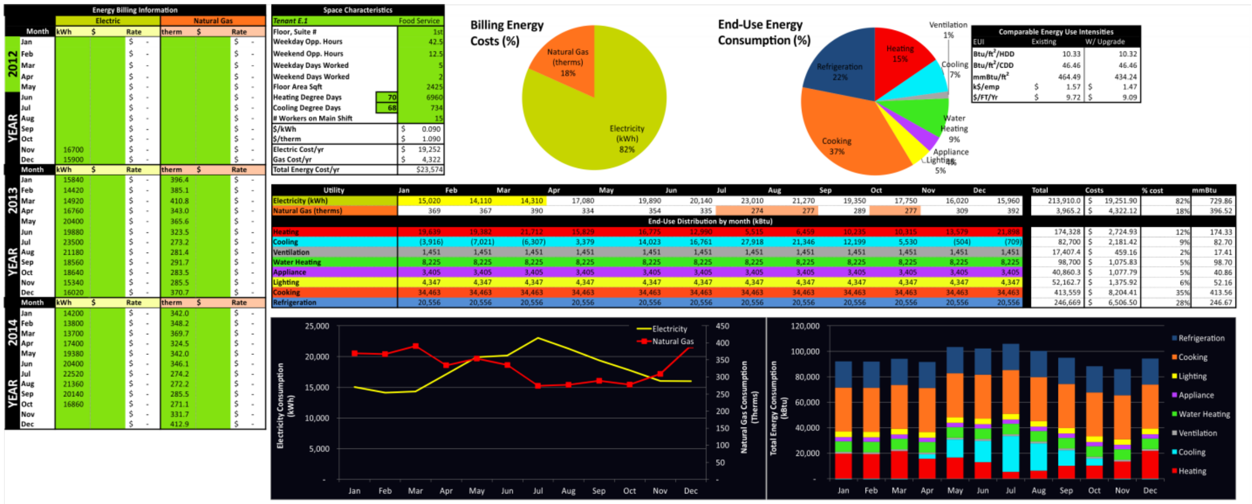
Comparable Energy Use Intensities

EUI	Existing	W/ Upgrade
Btu/ft²/HDD	15.70	15.58
Btu/ft²/CDD	16.14	16.14
mmBtu/ft²	166.26	150.66
k$/emp	$ 0.47	$ 0.42
$/FT/Yr	$ 2.60	$ 2.36

Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Costs	% cost	mmBtu
Electricity (kWh)	2,000	1,760	1,560	1,600	2,760	3,160	3,360	3,640	2,720	1,760	1,040	1,640	27,000.0	$ 2,430.00	52%	92.12
Natural Gas (therms)	164	651	512	225	49	5	-	-	-	-	64	401	2,071.5	$ 2,257.89	48%	207.15
End-Use Distribution by month (kBtu)																
Heating	16,442	65,122	51,257	22,501	4,937	518	2	3	8	10	6,377	40,063	207,238	$ 2,260.14	48%	207.24
Cooling	922	103	(579)	(443)	3,517	4,885	5,570	6,525	3,381	103	(2,354)	(307)	21,324	$ 562.48	12%	21.32
Ventilation	-	-	-	-	-	-	-	-	-	-	-	-	-			-
Water Heating	57	57	57	57	57	57	57	57	57	57	57	57	682	$ 18.00	0%	0.68
Appliance	3,806	3,806	3,806	3,806	3,806	3,806	3,806	3,806	3,806	3,806	3,806	3,806	45,676.8	$ 1,204.84	26%	45.68
Lighting	1,845	1,845	1,845	1,845	1,845	1,845	1,845	1,845	1,845	1,845	1,845	1,845	22,142.5	$ 584.06	12%	22.14
Cooking	-	-	-	-	-	-	-	-	-	-	-	-	-			-
Refrigeration	184	184	184	184	184	184	184	184	184	184	184	184	2,206	$ 58.18	1%	2.21

C.5 BEAR'S BUILDING INFORMATION INTERFACE (FOOD SERVICE)

Presented is a screen capture of the building information interface, where business operational information, employee headcount, floor area, energy bills, and energy costs are entered. Note: the line graph illustrates energy billing information for electricity (kWh) and natural gas (therms), while the bar graph depicts the reconciled energy profile (step 5) for the building space; green cells indicate fields requesting data entry, including business operational information and energy bills. The information entered in this example is that of Building E, tenant E.1, a restaurant.



Energy Billing Information

YEAR	Month	Electric kWh	Electric $	Electric Rate	Natural Gas therm	Natural Gas $	Natural Gas Rate
2012	Jan			$ -			$ -
	Feb			$ -			$ -
	Mar			$ -			$ -
	Apr			$ -			$ -
	May			$ -			$ -
	Jun			$ -			$ -
	Jul			$ -			$ -
	Aug			$ -			$ -
	Sep			$ -			$ -
	Oct			$ -			$ -
	Nov	16700		$ -			$ -
	Dec	15900		$ -			$ -
	Month	kWh	$	Rate	therm	$	Rate
2013	Jan	15840		$ -	396.4		$ -
	Feb	14420		$ -	385.1		$ -
	Mar	14920		$ -	410.8		$ -
	Apr	16760		$ -	343.0		$ -
	May	20400		$ -	365.6		$ -
	Jun	19880		$ -	323.5		$ -
	Jul	23500		$ -	273.2		$ -
	Aug	21180		$ -	281.4		$ -
	Sep	18560		$ -	291.7		$ -
	Oct	18640		$ -	283.5		$ -
	Nov	15340		$ -	285.5		$ -
	Dec	16020		$ -	370.7		$ -
	Month	kWh	$	Rate	therm	$	Rate
2014	Jan	14200		$ -	342.0		$ -
	Feb	13800		$ -	348.2		$ -
	Mar	13700		$ -	369.7		$ -
	Apr	17400		$ -	324.5		$ -
	May	19380		$ -	342.0		$ -
	Jun	20400		$ -	346.1		$ -
	Jul	22520		$ -	274.2		$ -
	Aug	21360		$ -	272.2		$ -
	Sep	20140		$ -	285.5		$ -
	Oct	16860		$ -	271.1		$ -
	Nov			$ -	331.7		$ -
	Dec			$ -	412.9		$ -

Space Characteristics

Tenant E.1		Food Service
Floor, Suite #		1st
Weekday Opp. Hours		42.5
Weekend Opp. Hours		12.5
Weekday Days Worked		5
Weekend Days Worked		2
Floor Area Sqft		2425
Heating Degree Days	70	6960
Cooling Degree Days	68	734
# Workers on Main Shift		15
$/kWh		$ 0.090
$/therm		$ 1.090
Electric Cost/yr		$ 19,252
Gas Cost/yr		$ 4,322
Total Energy Cost/yr		$23,574

Billing Energy Costs (%)

End-Use Energy Consumption (%)

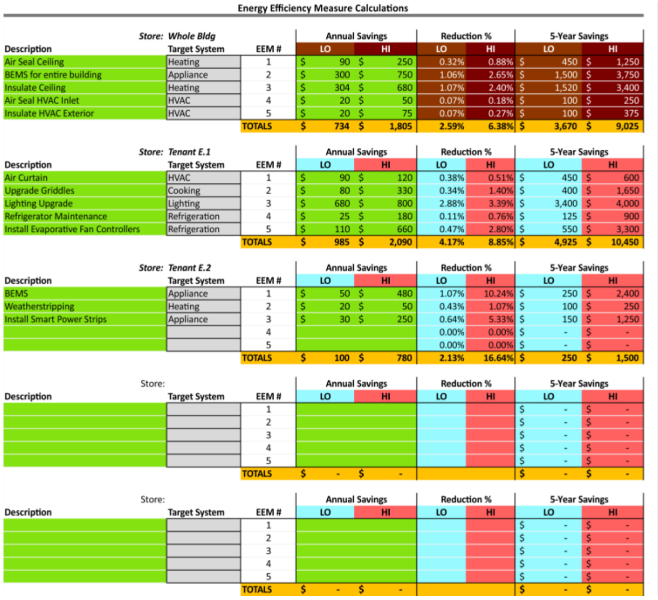
Comparable Energy Use Intensities

EUI	Existing	W/ Upgrade
Btu/ft²/HDD	10.33	10.32
Btu/ft²/CDD	46.46	46.46
mmBtu/ft²	464.49	434.24
k$/emp	$ 1.57	$ 1.47
$/FT/Yr	$ 9.72	$ 9.09

Utility	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total	Costs	% cost	mmBtu
Electricity (kWh)	15,020	14,110	14,310	17,080	19,890	20,140	23,010	21,270	19,350	17,750	16,020	15,960	213,910.0	$ 19,251.90	82%	729.86
Natural Gas (therms)	369	367	390	334	354	335	274	277	289	277	309	392	3,965.2	$ 4,322.12	18%	396.52
End-Use Distribution by month (kBtu)																
Heating	19,639	19,382	21,712	15,829	16,775	12,990	5,515	6,459	10,235	10,315	13,579	21,898	174,328	$ 2,724.93	12%	174.33
Cooling	(3,916)	(7,021)	(6,307)	3,379	14,023	16,761	27,918	21,346	12,199	5,530	(504)	(709)	82,700	$ 2,181.42	9%	82.70
Ventilation	1,451	1,451	1,451	1,451	1,451	1,451	1,451	1,451	1,451	1,451	1,451	1,451	17,407.4	$ 459.16	2%	17.41
Water Heating	8,225	8,225	8,225	8,225	8,225	8,225	8,225	8,225	8,225	8,225	8,225	8,225	98,700	$ 1,075.83	5%	98.70
Appliance	3,405	3,405	3,405	3,405	3,405	3,405	3,405	3,405	3,405	3,405	3,405	3,405	40,860.3	$ 1,077.79	5%	40.86
Lighting	4,347	4,347	4,347	4,347	4,347	4,347	4,347	4,347	4,347	4,347	4,347	4,347	52,162.7	$ 1,375.92	6%	52.16
Cooking	34,463	34,463	34,463	34,463	34,463	34,463	34,463	34,463	34,463	34,463	34,463	34,463	413,559	$ 8,204.41	35%	413.56
Refrigeration	20,556	20,556	20,556	20,556	20,556	20,556	20,556	20,556	20,556	20,556	20,556	20,556	246,669	$ 6,506.50	28%	246.67

C.6 BEAR’S SAVINGS ENGINE

Presented is a screen capture of the Savings Engine, which provides an opportunity for users to identify and manually calculate energy savings associated with an energy efficiency improvement. Comparable information is provided to users in the form of energy use intensities (EUI) prior to and after energy efficiency improvements are identified, and a summary of individual spaces’ reconciled energy profiles in addition to the whole building portfolio. Note: Calculations are manual and users enter only the targeted energy efficiency improvement and cost savings associated.



Energy Efficiency Measure Calculations

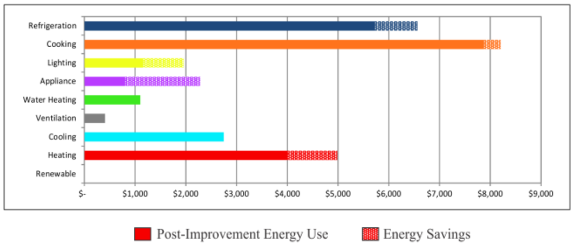
Store:	*Whole Bldg*		Annual Savings		Reduction %		5-Year Savings	
Description	Target System	EEM #	LO	HI	LO	HI	LO	HI
Air Seal Ceiling	Heating	1	$ 90	$ 250	0.32%	0.88%	$ 450	$ 1,250
BEMS for entire building	Appliance	2	$ 300	$ 750	1.06%	2.65%	$ 1,500	$ 3,750
Insulate Ceiling	Heating	3	$ 304	$ 680	1.07%	2.40%	$ 1,520	$ 3,400
Air Seal HVAC Inlet	HVAC	4	$ 20	$ 50	0.07%	0.18%	$ 100	$ 250
Insulate HVAC Exterior	HVAC	5	$ 20	$ 75	0.07%	0.27%	$ 100	$ 375
		TOTALS	$ 734	$ 1,805	2.59%	6.38%	$ 3,670	$ 9,025

Store:	*Tenant E.1*		Annual Savings		Reduction %		5-Year Savings	
Description	Target System	EEM #	LO	HI	LO	HI	LO	HI
Air Curtain	HVAC	1	$ 90	$ 120	0.38%	0.51%	$ 450	$ 600
Upgrade Griddles	Cooking	2	$ 80	$ 330	0.34%	1.40%	$ 400	$ 1,650
Lighting Upgrade	Lighting	3	$ 680	$ 800	2.88%	3.39%	$ 3,400	$ 4,000
Refrigerator Maintenance	Refrigeration	4	$ 25	$ 180	0.11%	0.76%	$ 125	$ 900
Install Evaporative Fan Controllers	Refrigeration	5	$ 110	$ 660	0.47%	2.80%	$ 550	$ 3,300
		TOTALS	$ 985	$ 2,090	4.17%	8.85%	$ 4,925	$ 10,450

Store:	*Tenant E.2*		Annual Savings		Reduction %		5-Year Savings	
Description	Target System	EEM #	LO	HI	LO	HI	LO	HI
BEMS	Appliance	1	$ 50	$ 480	1.07%	10.24%	$ 250	$ 2,400
Weatherstripping	Heating	2	$ 20	$ 50	0.43%	1.07%	$ 100	$ 250
Install Smart Power Strips	Appliance	3	$ 30	$ 250	0.64%	5.33%	$ 150	$ 1,250
		4			0.00%	0.00%	$ -	$ -
		5			0.00%	0.00%	$ -	$ -
		TOTALS	$ 100	$ 780	2.13%	16.64%	$ 250	$ 1,500

Store:			Annual Savings		Reduction %		5-Year Savings	
Description	Target System	EEM #	LO	HI	LO	HI	LO	HI
		1					$ -	$ -
		2					$ -	$ -
		3					$ -	$ -
		4					$ -	$ -
		5					$ -	$ -
		TOTALS	$ -	$ -			$ -	$ -

Store:			Annual Savings		Reduction %		5-Year Savings	
Description	Target System	EEM #	LO	HI	LO	HI	LO	HI
		1					$ -	$ -
		2					$ -	$ -
		3					$ -	$ -
		4					$ -	$ -
		5					$ -	$ -
		TOTALS	$ -	$ -			$ -	$ -



C.7 SUMMARY OF RESULTS FOR ANNUAL ENERGY CONSUMPTION

Annual energy consumption (MMBtu) for tenants comparing the BEAR mid-point estimate with collected energy bills. Note: Difference (%) is the absolute value of the difference between the sum of the mid-point estimates and energy bill divided by the energy bill; * denotes a Difference (%) that is negative; tenants are organized by smallest to largest total energy bill.

		Energy Consumption in MMBtu										
Building Activity	Ten-ant	Heat-ing	Cool-ing	Vent-ilation	Water Heat-ing	Light-ing	App-liance	Cook-ing	Refrig-eration	BEAR Est. Total	Total of Energy Bills	Diff-erence (%)
Food Service												
	G	23	10	0	15	9	13	16	160	246	267	10.0%*
	H.4	47	12	57	28	45	8	416	63	675	691	2.4%*
	F	502	60	0	31	39	13	402	134	1180	1045	7.3%
	E.1	216	79	17	99	52	41	414	247	1165	1126	1.6%
	J.1	231	38	51	47	74	61	735	93	1329	1494	0.3%
	H.1	63	35	98	29	176	71	1123	144	1739	1738	0.1%
	M	45	126	0	15	346	32	755	333	1653	1984	6.4%*
Office												
	C.2	70	6	0	0	11	14	0	1	102	145	13.5%*
	H.2	94	17	0	19	4	27	0	0	162	168	3.4%
	C.1	144	16	0	25	11	32	0	1	230	198	20.0%*
	B	75	16	1	8	28	66	0	2	196	199	6.5%*
	E.2	318	16	0	1	22	46	0	2	404	299	3.9%
	H.3	175	12	0	25	14	98	0	1	326	334	1.0%*
	K	64	16	0	29	37	272	0	2	421	419	0.7%
	D	133	119	0	1	97	41	0	2	393	444	13.7%*
	L	290	159	101	36	101	110	40	62	898	876	3.9%
Retail												
	A.3	27	0	0	0	3	1	0	1	33	36	8.8%*
	A.2	16	3	0	1	7	9	0	0	37	41	10.4%*
	A.1	74	23	0	16	31	101	0	5	250	264	5.0%*
	I	139	19	0	6	51	77	0	3	296	295	5.9%*

C.8 SUMMARY OF RESULTS FOR ANNUAL ELECTRICITY CONSUMPTION

Annual electricity consumption (MMBtu) for tenants comparing the BEAR mid-point estimate with collected electricity bills. Note: Difference (%) is the absolute value of the difference between the sum of the mid-point estimates and energy bill divided by the energy bill; * denotes a Difference (%) that is negative.

		Electricity Consumption in MMBtu										
Building Activity	Tenant	Heating	Cooling	Ventilation	Water Heating	Lighting	Appliance	Cooking	Refrigeration	BEAR Electric Total	Total of Electric Bills	Difference (%)
Food Service												
	G	0	10	0	0	9	13	16	160	208	231	10.0%*
	H.4	0	12	57	0	45	8	0	63	185	189	2.4%*
	F	67	60	0	0	39	13	70	134	382	356	7.3%
	E.1	66	79	17	0	52	41	239	247	741	730	1.6%
	J.1	0	38	51	16	74	61	86	93	418	417	0.3%
	H.1	0	35	98	0	176	71	69	144	593	594	0.1%
	M	0	126	0	0	346	32	586	333	1424	1521	6.4%*
Office												
	C.2	0	6	0	0	11	14	0	1	32	37	13.5%*
	H.2	0	17	0	0	4	27	0	0	49	47	3.4%
	C.1	0	16	0	0	11	32	0	1	61	76	20.0%*
	B	0	16	1	1	28	66	0	2	113	121	6.5%*
	E.2	9	16	0	1	22	46	0	2	96	92	3.9%
	H.3	0	12	0	0	14	98	0	1	125	126	1.0%*
	K	0	16	0	0	37	272	0	2	328	325	0.7%
	D	0	119	0	1	97	41	0	2	260	301	13.7%*
	L	2	159	101	0	101	110	10	62	544	524	0.4%
Retail												
	A.3	27	0	0	0	3	1	0	1	33	36	8.8%*
	A.2	16	3	0	1	7	9	0	0	37	41	10.4%*
	A.1	74	23	0	16	31	101	0	5	250	264	5.0%*
	I	0	19	0	0	51	77	0	3	151	160	5.9%*

C.9 SUMMARY OF RESULTS FOR ANNUAL NATURAL GAS CONSUMPTION

Annual natural gas consumption (MMBtu) for tenants comparing the BEAR mid-point estimate with collected natural gas bills. Note: Difference (%) is the absolute value of the difference between the sum of the mid-point estimates and energy bill divided by the energy bill; * denotes a Difference (%) that is negative.

		Natural Gas Consumption in MMBtu										
Building Activity	Tenant	Heating	Cooling	Ventilation	Water Heating	Lighting	Appliance	Cooking	Refrigeration	BEAR Natural Gas Total	Total of Natural Gas Bills	Difference (%)
Food Service												
	G	23	0	0	15	0	0	0	0	38	35	7.4%
	H.4	47	0	0	28	0	0	416	0	490	502	2.3%*
	F	435	0	0	31	0	0	332	0	798	689	15.7%
	E.1	150	0	0	99	0	0	175	0	423	397	6.8%
	J.1	231	0	0	31	0	0	649	0	911	1077	15.4%*
	H.1	63	0	0	29	0	0	1054	0	1146	1144	0.2%
	M	45	0	0	15	0	0	169	0	229	463	50.5%*
Office												
	C.2	70	0	0	0	0	0	0	0	70	108	34.8%*
	H.2	94	0	0	19	0	0	0	0	113	121	6.8%*
	C.1	144	0	0	25	0	0	0	0	170	122	38.6%
	B	75	0	0	8	0	0	0	0	83	78	6.6%
	E.2	309	0	0	0	0	0	0	0	309	207	49.0%
	H.3	175	0	0	25	0	0	0	0	201	208	3.4%*
	K	64	0	0	29	0	0	0	0	93	94	0.6%*
	D	133	0	0	0	0	0	0	0	133	143	6.8%*
	L	288	0	0	36	0	0	30	0	354	353	0.4%
Retail												
	A.3	0	0	0	0	0	0	0	0	0	0	-
	A.2	0	0	0	0	0	0	0	0	0	0	-
	A.1	0	0	0	0	0	0	0	0	0	0	-
	I	139	0	0	6	0	0	0	0	145	135	7.5%

C.10 CASE STUDY BUILDING INFORMATION

Below is a summation of the count of appliances and equipment operating on electric and natural gas, organized by enterprise type and tenant. Note: for Type 1 = Food Service, 2 = Office, and 3 = Retail.

			Electric Components (Count)								Natural Gas Components (Count)							
Type	Tenant	Floor Area (sqft)	Heating	Cooling	Ventilation	Water Heating	Lighting	Appliance	Cooking	Refrigeration	Heating	Cooling	Ventilation	Water Heating	Lighting	Appliance	Cooking	Refrigeration
1	E.1	2425	1	4	1	0	78	10	9	13	2	0	0	1	0	0	1	0
1	F	6354	1	1	0	0	48	14	2	10	2	0	0	1	0	0	4	0
1	G	894	0	1	0	0	24	5	6	10	1	0	0	1	0	0	0	0
1	H.1	1800	0	5	1	0	186	41	4	14	1	0	0	1	0	0	5	0
1	H.4	1016	0	1	1	0	67	7	0	7	1	0	0	1	0	0	4	0
1	J.1	5250	0	3	1	1	155	52	4	19	3	0	0	1	0	0	3	0
1	M	25000	0	5	0	0	935	29	53	47	1	0	0	1	0	0	11	0
2	B	5200	0	2	1	1	128	41	0	2	2	0	0	1	0	0	0	0
2	C.1	3800	0	2	0	0	60	39	0	0	2	0	0	1	0	0	0	0
2	C.2	1900	0	1	0	0	60	16	0	0	1	0	0	0	0	0	0	0
2	D	5290	0	2	0	1	81	62	0	2	2	0	0	0	0	0	0	0
2	E.2	3300	4	2	0	1	64	63	0	1	2	0	0	0	0	0	0	0
2	H.2	986	0	1	0	0	15	12	0	0	1	0	0	1	0	0	0	0
2	H.3	3850	0	2	0	0	50	68	0	1	2	0	0	1	0	0	0	0
2	K	2500	0	2	0	0	142	33	0	0	1	0	0	1	0	0	0	0
2	L	17230	1	4	4	0	432	71	5	11	3	0	0	2	0	0	3	0
3	A.1	1190	4	4	0	3	100	15	0	2	0	0	0	0	0	0	0	0
3	A.2	315	1	1	0	1	16	2	0	0	0	0	0	0	0	0	0	0
3	A.3	400	1	0	0	0	6	2	0	0	0	0	0	0	0	0	0	0

APPENDIX D

SUPPORTING INFORMATION FOR EVALUATION OF THE SOURCES AND MEASURE OF UNCERTAINTY IN APPLIANCE-LEVEL ELECTRICITY ENERGY ESTIMATE RESOURCES IN A FOOD SERVICE AND OFFICE SMALL COMMERCIAL BUILDING

Supporting information for the evaluation of the sources and measure of uncertainty in BEAR's appliance-level calculations is presented below. Included in the supporting information are the list of components and corresponding smart meter identifier, daily energy and modal power estimates calculated from the bootstrap analysis, and additional energy contour plots for twelve appliances, intended as a representative sample of those evaluated, are included below.

D.1 LIST OF COMPONENTS AND SMART METER IDENTIFIER

A complete list of appliances metered, organized by smart meter identifier. Multiple appliances listed under a single smart meter identifier indicates a power strip.

Enter-prise	Smart Meter Identifier	Component Identifier	Taxonomy
A	Three Pot Warmer	Three Pot Warmer	Commercial Food Handling
	Commercial Freezer	Commercial Freezer	Commercial Food Handling
	French Fry Warmer	French Fry Warmer	Commercial Food Handling
	Amplifier (1st Floor)	Amplifier (1st Floor)	Audio/Video
	Power Strip (workstation)	UPS system	Workstation
		Portable device charger	Personal
		Ethernet Switch	Networking
		Computer Monitor	Workstation
		Wireless Gateway	Networking
		Computer Tower	Workstation
	Neon Window Sign	Neon Window Sign	Accent Lighting
	Power Strip (POS)	POS Monitor	POS Station
		POS Ticket Printer	POS Station
		Portable device charger	Personal
		Credit Card Reader	POS Station
	DVR Router	DVR Router	Audio/Video
	Amplifier (basement)	Amplifier (basement)	Audio/Video
	Cable Box	Cable Box	Audio/Video
	POS Monitor (bar)	POS Monitor (bar)	POS Station
	POS Ticket Printer (bar)	POS Ticket Printer (bar)	POS Station
	Fax Modem	Fax Modem	Networking
B	Microwave	Microwave	Office Food Handling
	12-cup Coffee Maker	12-cup Coffee Maker	Office Food Handling
	Refrigerator	Refrigerator	Office Food Handling
	Kitchenette	Single Serve Coffee Maker	Office Food Handling
		Toaster Oven	Office Food Handling
		Toaster	Office Food Handling
	Hole Punch	Hole Punch	Workstation
	Copier	Copier	Workstation
	Desk 1 Tower	Computer Tower	Workstation
	Desk 3	Computer Monitor	Workstation
		Computer Tower	Workstation
		Computer Monitor	Workstation
		Desk Lamp	Task Lighting
	Desk 4a	Computer Monitor	Workstation
		Computer Tower	Workstation
	Desk 4b	Computer Monitor	Workstation
		Computer Tower	Workstation
	Desk 4a Tower	Computer Tower	Workstation
	Desk 4b Tower	Computer Tower	Workstation
	Desk 4 Monitor	Computer Monitor	Workstation
	Desk 5	Computer Monitor	Workstation
		Computer Monitor	Workstation
		Computer Tower	Workstation
	Desk 6	Computer Monitor	Workstation
		Computer Monitor	Workstation
		Computer Tower	Workstation

D.2 DAILY ENERGY USE ESTIMATES USED IN BEAR AND CALCULATED FROM BOOTSTRAP ANALYSIS

Daily energy use estimates from BEAR and bootstrap analysis of smart meter measured appliances compartmentalized into weekday and weekend use. Resource refers to the method(s) of quantifying energy consumption for each smart meter in BEAR: 1 – Energy Star Database (Energy Star 2016), 2 - Energy Star Office Equipment Calculator (Energy Star 2016), 3 - Energy Star Appliance Calculator (Energy Star 2016), 4 - Manufacturer's label, and 5 – generalized assumption because appliance-specific data was not available.

Enter-prise	Monitor Identifier	Bootstrap Mean Energy (Wh/day)		BEAR Wt. Avg. Energy (Wh/day)		Deviation		Res.
		Wkday	Wkend	Wkday	Wkend	Wkday	Wkend	
A	Three Pot Warmer	7,937	7,355	21,606	21,606	172%	194%	4
	Commercial Freezer	10,056	n/a	6,280	6,280	-38%	n/a	1
	French Fry Warmer	5,649	5,777	7,509	7,509	33%	30%	4
	Amplifier (1st Floor)	1,618	1,382	1,260	1,260	-22%	-9%	4
	Power Strip (workstation)	2,035	2,057	2,165	3,214	6%	56%	2, 4, 5
	Neon Window Sign	787	817	702	702	-11%	-14%	4
	Power Strip (POS)	403	406	657	657	63%	62%	4
	DVR Router	541	561	270	270	-50%	-52%	4
	Amplifier (basement)	433	432	480	480	11%	11%	4
	Cable Box	317	317	432	432	36%	36%	4
	POS Monitor (bar)	193	195	517	517	168%	166%	4
	POS Ticket Printer (bar)	39	39	44	44	13%	14%	4
	Fax Modem	86	86	48	48	-44%	-44%	4
B	Microwave	323	86	311	48	-4%	-44%	4
	12-cup Coffee Maker	98	0	1,896	0	1843%	-100%	4
	Refrigerator	1,511	1,359	994	994	-34%	-27%	3
	Kitchenette	300	79	2,235	114	645%	45%	4
	Hole Punch	29	29	24	24	-17%	-17%	4
	Copier	462	230	265	264	-43%	15%	4
	Desk 1 Tower	663	298	712	41	7%	-86%	2
	Desk 3	1,272	306	1,521	221	20%	-28%	2
	Desk 4a	1,202	58	1,044	59	-13%	2%	2
	Desk 4b	639	58	1,044	59	63%	2%	1, 2
	Desk 4a Tower	1,000	0	712	41	-29%	n/a	2
	Desk 4b Tower	430	0	336	7	-22%	n/a	1, 2
	Desk 4 Monitor	120	0	332	18	178%	n/a	2
	Desk 5	2,439	763	1,358	45	-44%	-94%	1, 2
	Desk 6	1,099	276	1,377	77	25%	-72%	2

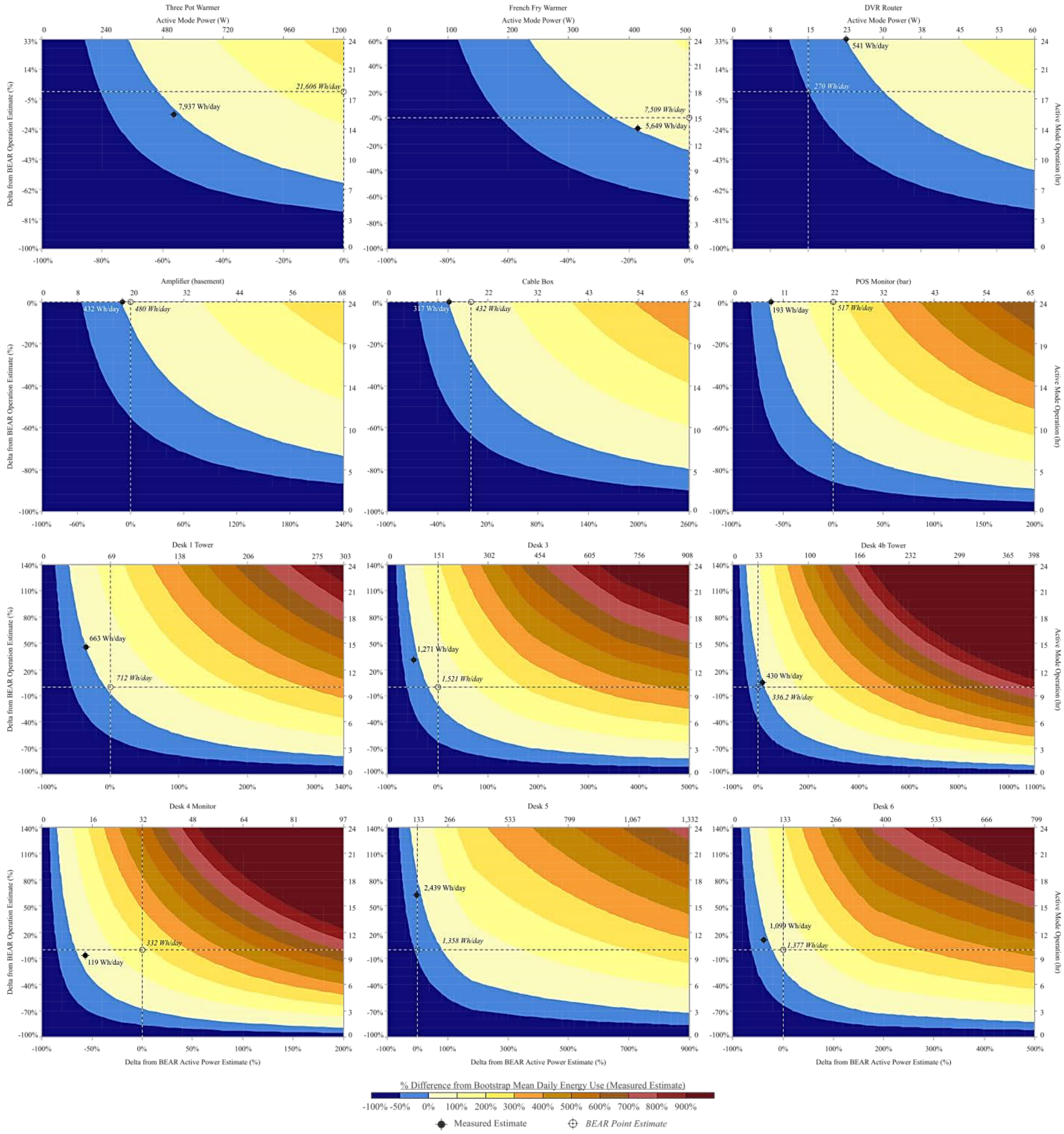
D.3 ACTIVE MODE POWER ESTIMATES USED IN BEAR AND CALCULATED FROM BOOTSTRAP ANALYSIS

Active mode power estimates from the bootstrap analysis of smart meter measured appliances and BEAR input parameters. It is assumed that appliance use during business hours is 100% attributed to active mode. An (*) means a bootstrap analysis was not performed.

Enter-prise	Monitor Identifier	Bootstrap Mean Power during Business Hours (Active Mode)	BEAR Power Input (Active Mode)	Error	Modal Information Available?
A	Three Pot Warmer	462.5	1200.0	159%	No
	Commercial Freezer	463.6	261.7	-44%	Yes
	French Fry Warmer	336.5	500.0	49%	Yes
	Amplifier (1st Floor)	83.6	725.0	767%	No
	Power Strip (work station)	85.5	129.0	51%	Yes
	Neon Window Sign	45.4	29.3	-36%	Yes
	Power Strip (POS)	17.6	68.1	287%	No
	DVR Router	22.2	15.0	-32%	Yes
	Amplifier (basement)	18.0	20.0	11%	Yes
	Cable Box	13.2	18.0	36%	Yes
	POS Monitor (bar)	8.7	21.6	148%	No
	POS Ticket Printer (bar)	1.7	21.6	1132%	No
	Fax Modem	3.6	4.0	11%	Yes
B	Microwave	*	1580.0	n/a	Yes
	12-cup Coffee Maker	*	1775.0	n/a	No
	Refrigerator	70.6	41.4	-41%	Yes
	Kitchenette	*	4575.0	n/a	No
	Hole Punch	1.2	1.3	4%	No
	Copier	29.6	19.5	-34%	Yes
	Desk 1 Tower	40.7	68.8	69%	Yes
	Desk 3	99.7	151.2	52%	Yes
	Desk 4a	89.9	101.0	12%	Yes
	Desk 4b	49.3	101.0	105%	Yes
	Desk 4a Tower	74.6	68.8	-8%	Yes
	Desk 4b Tower	34.0	33.2	-2%	Yes
	Desk 4 Monitor	10.3	32.2	213%	Yes
	Desk 5	178.3	133.2	-25%	Yes
	Desk 6	96.6	133.2	38%	Yes

D.4 ADDITIONAL ENERGY CONTOUR PLOTS

In the energy contour plots, the horizontal axis is the appliance active mode power demand and is put in terms of percent difference from the BEAR estimated power (bottom horizontal axis) and in watts (top horizontal axis). The vertical axis is the appliance active mode operational time and is put in terms of percent difference from the BEAR estimated operation (left vertical axis) and in hours (right vertical axis). Contour plots were created from the smart meter measured data. The bootstrap statistical average daily energy use of each appliance is the line that forms at the meeting of the blue and white regions. The black dot represents the estimated actual daily energy use as determined through cumulative distribution functions. The estimated daily energy use derived from BEAR is plotted as an open circle with lines connecting to each of the four axes.


Three Pot Warmer
French Fry Warmer
DVR Router
Amplifier (basement)
Cable Box
POS Monitor (bar)
Desk 1 Tower
Desk 3
Desk 4b Tower
Desk 4 Monitor
Desk 5
Desk 6
Active Mode Power (W)
Active Mode Operation (hr)
Delta from BEAR Operation Estimate (%)
Delta from BEAR Active Power Estimate (%)
7,937 Wh/day
21,606 Wh/day
7,509 Wh/day
5,649 Wh/day
541 Wh/day
270 Wh/day
432 Wh/day
480 Wh/day
317 Wh/day
432 Wh/day
193 Wh/day
517 Wh/day
663 Wh/day
712 Wh/day
1,271 Wh/day
1,521 Wh/day
430 Wh/day
336.2 Wh/day
332 Wh/day
119 Wh/day
2,439 Wh/day
1,358 Wh/day
1,090 Wh/day
1,377 Wh/day
% Difference from Bootstrap Mean Daily Energy Use (Measured Estimate)
-100% -50% 0% 100% 200% 300% 400% 500% 600% 700% 800% 900%
Measured Estimate
BEAR Point Estimate

BIBLIOGRAPHY

2030 Districts (2012). "Pittsburgh 2030 District." Retrieved January 5, 2014, from www.2030districts.org/pittsburgh.

A. Astin, et al. (2000). How service based learning affects students. Higher Education Research Institute. University of California, Los Angeles, CA.

ABET (2015). "Criteria for Accrediting Engineering Programs, 2016 – 2017." Retrieved November 9, 2015, from http://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2016-2017.

ABET (2016). "ABET: Accreditation Board for Engineering and Technology." Retrieved September 12, 2016, from http://www.abet.org/.

ABET (2016). "Mutual Recognition Agreements." Retrieved September 12, 2016, from http://www.abet.org/global-presence/mutual-recognition-agreements/.

Abrahamse, W., et al. (2005). "A review of intervention studies aimed at household energy conservation." Journal of Environmental Psychology **25**(3): 273-291.

Achtnicht, M. and R. Madlener (2014). "Factors influencing German house owners' preferences on energy retrofits." Energy Policy **68**: 254-263.

Ahmad, M. W., et al. (2016). "Building energy metering and environmental monitoring – A state-of-the-art review and directions for future research." Energy and Buildings **120**: 85-102.

Akbari, H. (1995). "Validation of an algorithm to disaggregate whole-building hourly electrical load into end uses." Energy **20**(12): 1291-1301.

Allen, D., et al. (2008). Benchmarking sustainable engineering education: Final report. Benchmarking Sustainable Engineering Education. Washington, DC, U.S. Environmental Protection Agency.

Allenby, B., et al. (2009). "Sustainable engineering education in the United States." Sustainability Science **4**(1): 7-15.

Anderson, L. W., et al. (2001). A taxonomy for learning, teaching, and assessing: A revision of Bloom's taxonomy of educational objectives, Allyn & Bacon.

Antaya, C. L., et al. (2013). Incorporating Sustainability into the Civil Engineering curriculum via cross course collaborations. American Society for Engineering Education, Atlanta, GA.

Architecture 2030 (2016). "Architecture 2030." Retrieved July 14, 2016, from http://architecture2030.org/.

Argonne National Laboratory (2011). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. version 1.8c. http://greet.es.anl.gov/main.

Armel, C. K., et al. (2013). "Is disaggregation the holy grail of energy efficiency? The case of electricity." Energy Policy **52**: 213-234.

ASCE (2004). Civil Engineering Body of Knowledge for the 21st Century: Preparing the Civil Engineer for the Future, 1st Edition. C. o. A. P. f. P. P. B. o. K. Committee, American Society of Civil Engineers.

ASCE (2008). Civil Engineering Body of Knowledge for the 21st Century: Preparing the Civil Engineer for the Future, 2nd Edition. Committee on Academic Prerequisites for Professional Practice. Body of Knowledge Committee, American Society of Civil Engineers.

ASCE (2016). "ASCE: American Society of Civil Engineers." Retrieved September 12, 2016, from http://www.asce.org/.

ASCE (2016). "Membership and Communisties." Retrieved September 11, 2016, from http://www.asce.org/membership-communities/.

ASCE (2016). "Raise the Bar for Engineering." Retrieved September 11, 2016, from http://www.raisethebarforengineering.org/.

ASEE (2016). "ASEE Interdivisional Town Hall Meetings." Virtual Conference. Retrieved March 8, 2016, from https://aseetownhall.wordpress.com/virtual-conference/.

ASEE (2016). "A Summary of the Virtual Conference on Proposed Changes to ABET Engineering Accreditation Standards." Retrieved September 9, 2016, from https://www.asee.org/documents/about-us/our-partners/premier-corporate-partners/abet/Summary-VC-Comments.pdf.

ASHRAE (2011). Procedures For Commercial Building Energy Audits.

ASHRAE (2013). ANSI/ASHRAE/IES Standard 90.1-2013 - Energy Standard for Buildings Except Low-Rise Residential Buildings. 1791 Tullie Circle, NE, Atlanta, GA 30329, American Society for Heating, Refrigerating an Air-Conditioning Engineers, Inc. **ISSN 1041-2336**.

Atkins, R. (2015). "Commitment to President Obama: 20,000 GRAND CHALLENGE ENGINEERS in a decade Schools will specially prepare new generation to take on societal aspirations." Retrieved September 12, 2016, from http://www.engineeringchallenges.org/14373/15549/15785.aspx.

Aurandt, J. L. and E. C. Butler (2011). "Sustainability Education: Approaches for Incorporating Sustainability into the Undergraduate Curriculum." **137**: 102-106.

Bacon, C. M., et al. (2011). "The Creation of an Integrated Sustainability Curriculum and Student Praxis Projects." International Journal of Sustainability in Higher Education **12**(2): 193-208.

Barbose, G. L., et al. (2013). The Future of Utility Customer-Funded Energy Efficiency Programs in the United States: Projected Spending and Savings to 2025, U.S. DOE, Berkeley Lab,**:** 1-53.

Barnes, E. and K. Parrish (2015). "Small Buildings, Big Impacts: Developing a Library of Small Commercial Building Energy Efficiency Case Studies." Procedia Engineering **118**: 853-860.

Barnes, E. and K. Parrish (2016). "Small buildings, big impacts: The role of small commercial building energy efficiency case studies in 2030 Districts." Sustainable Cities and Society **27**: 210-221.

Barr, S., et al. (2005). "The household energy gap: examining the divide between habitual- and purchase-related conservation behaviours." Energy Policy **33**(11): 1425-1444.

Barry, B. and M. Ohland (2012). "ABET Criterion 3.f: How Much Curriculum Content is Enough?" Science & Engineering Ethics **18**(2): 369-392.

Bellingham, A., et al. (2016). The Impact of Project-based Learning on Engagement as a Function of Student Demographics. 123rd ASEE Annual Conference and Exposition. New Orleans, LA.

Berges, M. E., et al. (2010). "Enhancing electricity audits in residential buildings with nonintrusive load monitoring." Journal of Industrial Ecology **14**(5): 844-858.

Berkeley Lab (2014). "Standby Power." Retrieved March 1, 2014, from www.standby.lbl.gov/standby.html.

Bielefeldt, A. (2011). "Incorporating a Sustainability Module into First-Year Courses for Civil and Environmental Engineering Students." Journal of Professional Issues in Engineering Education and Practice **137**(2): 78-85.

Bielefeldt, A. (2013). "Pedagogies to achieve sustainability learning outcomes in civil and environmental engineering students." Sustainability **5**(10): 4479-4501.

Bilec, M. M., et al. (2011). Updating the Benchmark Sustainable Engineering Education Report: Trends from 2005 to 2010. 118th ASEE Annual Conference and Exposition, Vancouver, BC.

Birt, B. J., et al. (2012). "Disaggregating categories of electrical energy end-use from whole-house hourly data." Energy and Buildings **50**(0): 93-102.

Bloom, B. S. (1964). Stability and change in human characteristics. New York, Wiley.

Bloom, B. S., et al. (1956). Taxonomy of educational objectives: Handbook I: Cognitive domain.

Boks, C. and J. C. Diehl (2006). "Integration of sustainability in regular courses: experiences in industrial design engineering." Journal of Cleaner Production **14**(9–11): 932-939.

Boyle, C. (2004). "Considerations on Educating Engineers in Sustainability." International Journal of Sustainability in Higher Education **5**(2): 147-155.

Brown, S., et al. (2015). "Civil Engineering Faculty Incorporation of Sustainability in Courses and Relation to Sustainability Beliefs." Journal of Professional Issues in Engineering Education and Practice **141**(2): C4014005.

Bruel, R. and J. Hoekstra (2005). How to stimulate owner-occupiers to save energy. ECEEE Summer Study Proceedings.

Brumbelow, K., et al. (2015). Transformation of a large civil engineering department curriculum using the ASCE BOK2. 122nd ASEE Annual Conference and Exposition**:** 1-21.

Brundiers, K. and A. Wiek (2011). "Educating Students in Real-world Sustainability Research: Vision and Implementation." Innovative Higher Education **36**(2): 107-124.

Brunsell, E. and M. Horejsi (2013). "A flipped classroom in action." The Science Teacher **80**(2): 8.

Burman, E., et al. (2014). "A comparative study of benchmarking approaches for non-domestic buildings: Part 2 – Bottom-up approach." International Journal of Sustainable Built Environment **3**(2): 247-261.

Cagno, E. and A. Trianni (2013). "Exploring drivers for energy efficiency within small- and medium-sized enterprises: First evidences from Italian manufacturing enterprises." Applied Energy **104**(0): 276-285.

Camilleri, M., et al. (2006). Standby and Baseload in New Zealand Houses: A Nationwide Statistically Representative Study. 2006 ACEEE Summer Study on Energy Efficiency in Buildings, Pacific Grove, CA.

Carter, D. (2011). "What is service learning article." Retrieved November 7, 2014, from https://gsn.nylc.org/projects/333/documents/578.

Cattano, C., et al. (2011). "Teaching Systems Thinking and Biomimicry to Civil Engineering Students." Journal of Professional Issues in Engineering Education & Practice **137**(4): 176-182.

Cavalli, M., et al. (2014). Comparison of student performance and perceptions across multiple course delivery modes. 121st ASEE Annual Conference and Exposition.

CEC (2017). "Appliance Efficiency Database." Retrieved February 20, 2017, from www.cacertappliances.energy.ca.gov/Pages/ApplianceSearch.aspx.

Ceulemans, K. and M. De Prins (2010). "Teacher's manual and method for SD integration in curricula." Journal of Cleaner Production **18**(7): 645-651.

Chahine, K., et al. (2011). "Electric Load Disaggregation in Smart Metering Using a Novel Feature Extraction Method and Supervised Classification." Energy Procedia **6**: 627-632.

Chau, K. W. (2007). "Incorporation of Sustainability Concepts into a Civil Engineering Curriculum." Journal of Professional Issues in Engineering Education & Practice **133**(3): 188-191.

Christ, J. A., et al. (2015). "Incorporating Sustainability and Green Engineering into a Constrained Civil Engineering Curriculum." Journal of Professional Issues in Engineering Education & Practice **141**(2).

Christiansen, N., et al. (2015). "Electricity consumption of medical plug loads in hospital laboratories: Identification, evaluation, prediction and verification." Energy and Buildings **107**: 392-406.

Chrysopoulos, A., et al. (2014). "Bottom-up modeling of small-scale energy consumers for effective Demand Response Applications." Engineering Applications of Artificial Intelligence **35**(0): 299-315.

Coll, R. K., et al. (2002). "An Application of the Questionnaire on Teacher Interaction and College and University Classroom Environment Inventory in a Multicultural Tertiary Context." Research in Science and Technological Education **20**(2): 165-183.

Crawley, D. B., et al. (2008). "Contrasting the capabilities of building energy performance simulation programs." Building and Environment **43**(4): 661-673.

Crawley, D. B., et al. (2001). "EnergyPlus: creating a new-generation building energy simulation program." Energy and Buildings **33**(4): 319-331.

D. Riley, et al. (2012). Process Performance Evaluation of Home Energy Assessment Procedures. Building America NELC-(1)**:** 8-12.

Dancz, C. L. A., et al. (2017 accepted). "Utilizing Civil Engineering Senior Design Capstone Projects to Evaluate Students' Sustainability Education Across Engineering Curriculum." Advances in Engineering Education.

Dancz, C. L. A., et al. (2016). A Rubric to Assess Civil Engineering Students' Grand Challenge Sustainable Entrepreneurship Projects. 123rd ASEE Annual Conference and Exposition. New Orleans, LA.

Davidson, C. I., et al. (2010). "Preparing future engineers for challenges of the 21st century: Sustainable engineering." Journal of Cleaner Production **18**(7): 698-701.

de Groot, H. L. F., et al. (2001). "Energy saving by firms: decision-making, barriers and policies." Energy Economics **23**(6): 717-740.

Desroches, L.-B., et al. (2014). Computer usage and national energy consumption: Results from a field-metering study. Berkeley, CA, U.S. DOE, LBNL.

Dukhan, N., et al. (2008). "Implementation of service-learning in engineering and its impact on students' attitudes and identity." European Journal of Engineering Education **33**(1): 21-31.

Dunbabin, P., et al. (2015). Electricity use by domestic appliances in English households. ECEEE-2015 European council for an energy efficient economy. Hyeres, France.

Dutta, P. and A. Haubold (2007). Engineering design via team-based service-learning projects: Case survey of five unique project genres. 114th ASEE Annual Conference and Exposition, Honolulu, Hawaii.

Energy Star (2014). ENERGY STAR Program Requirements for Computers v6.1 – Partner Commitments.

Energy Star (2016). "Certified Product Database." Retrieved July 7, 2016, from https://data.energystar.gov/.

Energy Star (2016). "Certified Products." Retrieved July 7, 2016, from https://www.energystar.gov/products.

Energy Star (2016, October 2016). "Savings Calculator for ENERGY STAR-Qualified Appliances." Retrieved January 31, 2017, from https://www.energystar.gov/sites/default/files/asset/document/appliance_calculator.xlsx.

Energy Star (2016, October 2016). "Savings Calculator for ENERGY STAR-Qualified Office Equipment." Retrieved January 31, 2017, from https://www.energystar.gov/sites/default/files/asset/document/Office%20Equipment%20Calculator.xlsx.

Estes, A. C., et al. (2016). Accreditation Insights and the Next Body of Knowledge. 123rd ASEE Annual Conference and Exposition. New Orleans, LA.

Evans, J. C. and M. O. Beiler (2015). Humanities and Social Sciences Outcomes for the Third Edition: Civil Engineering Body of Knowledge. 122nd ASEE Annual Conference & Exposition. Seattle, WA.

Farinaccio, L. and R. Zmeureanu (1999). "Using a pattern recognition approach to disaggregate the total electricity consumption in a house into the major end-uses." Energy and Buildings **30**(3): 245-259.

Field, J., et al. (1997). "Energy performance of occupied non-domestic buildings: Assessment by analysing end-use energy consumptions." Building Services Engineering Research & Technology **18**(1): 39-46.

First Lady Michelle Obama (2010). "Let's Move: America's Move to Raise a Healthier Generation of Kids." Retrieved May 15, 2015, from http://www.letsmove.gov/.

Fleiter, T., et al. (2012). "Adoption of energy-efficiency measures in SMEs—An empirical analysis based on energy audit data from Germany." Energy Policy **51**(0): 863-875.

Fogarty, R. (1991). "Ten Ways to Integrate Curriculum." Educational Leadership **October 1991**.

Fraser, B. J. and D. F. Treagust (1986). "Validity and Use of an Instrument for Assessing Classroom Psychosocial Environment in Higher Education." Higher Education **15**(1/2): 37-57.

Fresner, J., et al. (2017). "Energy efficiency in small and medium enterprises: Lessons learned from 280 energy audits across Europe." Journal of Cleaner Production **142**: 1650-1660.

Fridley, K. J., et al. (2012). The Raise the Bar Initiative: Response of Three Curricula to ASCE's Educational Recommendations. 119th ASEE Annual Conference and Exposition, San Antonio, TX.

Frondel, M. and C. Vance (2013). "Heterogeneity in the Effect of Home Energy Audits: Theory and Evidence." Environmental and Resource Economics **55**(3): 407-418.

FTC (2016). "Shopping for Home Appliances? Use the EnergyGuide Label." Retrieved December 8, 2016, from www.consumer.ftc.gov/articles/0072-shopping-home-appliances-use-energyguide-label.

Fuller, M. C., et al. (2010). Driving demand for home energy improvements, Lawrence Berkeley Nat. Lab.**:** 3960.

Gaetani, I., et al. (2016). "Occupant behavior in building energy simulation: Towards a fit-for-purpose modeling strategy." Energy and Buildings **121**: 188-204.

Galand, B., et al. (2010). "Engineering students' self-regulation, study strategies, and motivational believes in traditional and problem-based curricula." INTERNATIONAL JOURNAL OF ENGINEERING EDUCATION **26**(3): 523-534.

Gamtessa, S. F. (2013). "An explanation of residential energy-efficiency retrofit behavior in Canada." Energy and Buildings **57**(0): 155-164.

Gandhi, P. and G. S. Brager (2016). "Commercial office plug load energy consumption trends and the role of occupant behavior." Energy and Buildings **125**: 1-8.

GBA (2017). "Green Building Alliance." Retrieved February 9, 2017, from www.go-gba.org/.

Giri, S. and M. Bergés (2015). "An energy estimation framework for event-based methods in Non-Intrusive Load Monitoring." Energy Conversion and Management **90**: 488-498.

Goggins, J. (2012). "Engineering in communities: Learning by doing." Campus-Wide Information Systems **29**(4): 238-250.

Goodwin, B. and K. Miller (2013). "Evidence on flipped classrooms is still coming in." Educational Leadership **70**(6): 78-80.

Gram-Hanssen, K., et al. (2007). "Do homeowners use energy labels? A comparison between Denmark and Belgium." Energy Policy **35**(5): 2879-2888.

Gruber, E., et al. (2011). Efficiency of an Energy Audit programme for SMEs in Germany – Results of an Evaluation Study. ECEEE 2011 Summer Study Energy Efficiency First: The foundation of a low-carbon society, Belambra Presqu'île de Giens, France, Template Publishing.

Gunay, H. B., et al. (2016). "Modeling plug-in equipment load patterns in private office spaces." Energy and Buildings **121**: 234-249.

Gunnink, B. (2010). How The Civil Engineering BOK2 Can Be Implemented At Montana State University. 117th ASEE Annual Conference and Exposition. Louisville, Kentucky.

Gwet, K. L. (2014). Handbook of inter-rater reliability: The definitive guide to measuring the extent of agreement among raters, Advanced Analytics, LLC.

H.R.1 - 111th Congress (2009). American Recovery and Reinvestment Act of 2009.

H.R.6 - 110th Congress (2007). Energy Independence and Security Act of 2007.

H.R.776 - 102nd Congress (1992). Energy Policy Act of 1992.

Harish, V. S. K. V. and A. Kumar (2016). "A review on modeling and simulation of building energy systems." Renewable and Sustainable Energy Reviews **56**: 1272-1292.

He, Y., et al. (2012). "Online video tutorials increase learning of difficult concepts in an undergraduate analytical chemistry course." Journal of Chemical Education **89**(9): 1128-1132.

Hegarty, K., et al. (2011). "Insights into the value of a 'stand-alone' course for sustainability education." Environmental Education Research **17**(4): 451-469.

Heidell, J. A., et al. (1985). Commercial building end-use energy metering inventory, Pacific Northwest Laboratory. **Report PNL-5027**.

Hirst, E., et al. (1981). "Review of utility home energy audit programs." Energy **6**(7): 621-630.

Hirst, E. and M. Brown (1990). "Closing the efficiency gap: barriers to the efficient use of energy." Resources, Conservation and Recycling **3**(4): 267-281.

Hirst, E. and R. Goeltz (1985). "Comparison of actual energy savings with audit predictions for homes in the north central region of the U.S.A." Building and Environment **20**(1): 1-6.

Hong, T., et al. (2000). "Building simulation: an overview of developments and information sources." Building and Environment **35**(4): 347-361.

Hong, T. and H.-W. Lin (2013). Occupant behavior: impact on energy use of private offices. ASim 2012 - 1st Asia conference of International Building Performance Simulation Association, Ernest Orlando Lawrence Berkeley National Laboratory.

IEA (2015). Accelerating Energy Efficiency in Small and Medium-sized Enterprises: Powering SMEs to catalyse economic growth, OECD,**:** 81.

IEA (2016). "The Washington Accord." Retrieved February 10, 2015, from http://www.ieagreements.org/Washington-Accord/.

Ingle, A., et al. (2012). How Well Do Home Energy Audits Serve the Homeowner? 2012 ACEEE Summer Study on Energy Efficiency in Buildings, Fueling Our Future with Efficiency. Pacific Grove, CA.

Ingle, A., et al. (2012). Behavioral Perspectives on Home Energy Audits: The Role of Auditors, Labels, Reports, and Audit Tools on Homeowner Decision Making**:** Medium: ED.

IPCC (2014). Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. Geneva, Switzerland, IPCC,**:** 151.

Iyer, S. R., et al. (2015). "Energy disaggregation analysis of a supermarket chain using a facility-model." Energy and Buildings **97**: 65-76.

Jaffe, A. B. and R. N. Stavins (1994). "The Energy-Efficiency Gap: What Does It Mean?" Energy Policy **22**: 804-810.

Jaffe, A. B. and R. N. Stavins (1994). "The energy-efficiency gap: What does it mean?" Energy Policy **22**(10): 7.

Ji, Y. and P. Xu (2015). "A bottom-up and procedural calibration method for building energy simulation models based on hourly electricity submetering data." Energy **93, Part 2**: 2337-2350.

Ji, Y., et al. (2015). "HVAC terminal hourly end-use disaggregation in commercial buildings with Fourier series model." Energy and Buildings **97**: 33-46.

Jiji, L. M., et al. (2015). "Capstone Interdisciplinary Team Project: A Requirement for the MS in Sustainability Degree." International Journal of Sustainability in Higher Education **16**(2): 187-199.

Jonassen, D., et al. (2006). "Everyday Problem Solving in Engineering: Lessons for Engineering Educators." Journal of Engineering Education **95**(2): 139-151.

Kastner, I. and P. C. Stern (2015). "Examining the decision-making processes behind household energy investments: A review." Energy Research & Social Science **10**: 72-89.

Ketchman, K., et al. (2017). "Sustainable Engineering Cognitive Outcomes: Examining Different Approaches for Curriculum Integration." Journal of Professional Issues in Engineering Education and Practice **143**(3).

Ketchman, K., et al. (2016). "Evaluation of a Holistic Energy Assessment Program." Procedia Engineering **145**: 468-475.

Ketchman, K. J., et al. (2017 submitted). Synergizing Disparate Component-level Energy Resources into a Single Whole Building Tool to Support Energy Conservation Action in Small Commercial Buildings.

Ketchman, K. J., et al. (2017 submitted). "A Survey of Homeowners’ Motivations for the Adoption of Energy Efficiency Measures: Evaluating a Holistic Energy Assessment Program." Journal of Architectural Engineering.

Kim, Y.-J., et al. (2013). "Stochastic comparison between simplified energy calculation and dynamic simulation." Energy and Buildings **64**(0): 332-342.

Kipping, A. and E. Trømborg (2016). "Modeling and disaggregating hourly electricity consumption in Norwegian dwellings based on smart meter data." Energy and Buildings **118**: 350-369.

Kontokosta, C. E. (2016). "Modeling the energy retrofit decision in commercial office buildings." Energy and Buildings **131**: 1-20.

Kostka, G., et al. (2013). "Barriers to increasing energy efficiency: evidence from small-and medium-sized enterprises in China." Journal of Cleaner Production **57**(0): 59-68.

Krathwohl, D. R. (2010). "A Revision of Bloom's Taxonomy: An Overview." Theory Into Practice **41**(4): 212-218.

Krigger, J. and C. Dorsi (2009). Residential energy: cost savings and comfort for existing buildings. Helena, Mont, Saturn Resource Management.

Krosnick, J. A., et al. (2002). "The Impact of "No Opinion" Response Options on Data Quality: Non-Attitude Reduction or an Invitation to Satisfice?" The Public Opinion Quarterly **66**(3): 371-403.

Kubba, S. (2015). LEED v4 Practices, Certification, and Accreditation Handbook. US, Butterworth Heinemann.

Kuppig, V. D., et al. (2016). "Implementation of sustainability improvements at the facility level: Motivations and barriers." Journal of Cleaner Production **139**: 1529-1538.

Lage, M. J., et al. (2000). "Inverting the classroom: A gateway to creating an inclusive learning environment." Journal of Economic Education **31**(1): 30-43.

Lanzisera, S., et al. (2013). "Methods for detailed energy data collection of miscellaneous and electronic loads in a commercial office building." Building and Environment **65**(0): 170-177.

Lavelle, J. P. and L. J. Bottomley (2011). NAE Grand Challenges and Academic Culture in Engineering Education at NC State. 2011 ASEE Southeast Section Conference Charleston, South Carolina.

Leal Filho, W., et al. (2016). "Implementing and operationalising integrative approaches to sustainability in higher education: the role of project-oriented learning." Journal of Cleaner Production **133**: 126-135.

Lee, S. H., et al. (2015). "Energy retrofit analysis toolkits for commercial buildings: A review." Energy **89**: 1087-1100.

Lee, W. L., et al. (2003). "A Method to Assess the Energy Performance of Existing Commercial Complexes." Indoor and Built Environment **12**(5): 311-327.

Lemons, G., et al. (2011). "The Effects of Service-Based Learning on Meta-Cognitive Strategies During an Engineering Design Task." International Journal for Service Learning in Engineering **6**(2): 1-18.

Lewis, A., et al. (2015). "BIM Energy Modeling: Case Study of a Teaching Module for Sustainable Design and Construction Courses." Journal of Professional Issues in Engineering Education and Practice **141**(2): C5014005.

Lidgren, A., et al. (2006). "A systemic approach to incorporate sustainability into university courses and curricula." Journal of Cleaner Production **14**(9–11): 797-809.

List, G. (2010). How The Civil Engineering BOK2 Could Be Implemented At Nc State. 117th ASEE Annual Conference and Exposition. Louisville, Kentucky.

Lockrey, S. and K. Bissett Johnson (2013). "Designing pedagogy with emerging sustainable technologies." Journal of Cleaner Production **61**: 70-79.

Lozano, R. (2010). "Diffusion of sustainable development in universities' curricula: an empirical example from Cardiff University." Journal of Cleaner Production **18**(7): 637-644.

Lozano, R., et al. (2013). "Advancing Higher Education for Sustainable Development: international insights and critical reflections." Journal of Cleaner Production **48**: 3-9.

Lucon, O., et al. (2014). 2014: Buildings. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change O. Edenhofer, R. Pichs-Madruga, Y. Sokona et al. Cambridge University Press, Cambridge, United Kingdom.

M.C. Fuller, et al. (2010). Driving demand for home energy improvements, Lawrence Berkeley Nat. Lab.**:** 3960.

Marceau, M. L. and R. Zmeureanu (2000). "Nonintrusive load disaggregation computer program to estimate the energy consumption of major end uses in residential buildings." Energy Conversion and Management **41**(13): 1389-1403.

Marks, J., et al. (2014). "Understanding the Benefits of the Flipped Classroom in the Context of Sustainable Engineering." Proceedings of the ASEE Annual Conference & Exposition: 1-13.

Martinsson, J., et al. (2011). "Energy saving in Swedish households. The (relative) importance of environmental attitudes." Energy Policy **39**(9): 5182-5191.

Matsui, K., et al. (2015). "Disaggregation of Electric Appliance's Consumption Using Collected Data by Smart Metering System." Energy Procedia **75**: 2940-2945.

McCormick, M., et al. (2015). "Sustainable Engineering Assessment Using Rubric-Based Analysis of Challenge Question Responses." Journal of Professional Issues in Engineering Education & Practice **141**(2): C4014002.

McDougall, G. H. G., et al. (1982). "Residential Home Audits - An Empirical Analysis Of The EnerSave Program." Journal of Environmental Systems **12**(3): 265-278.

Mckeown, R. (2011). "Using rubrics to assess student knowledge related to sustainability a practitioner's view." Journal of Education for Sustainable Development **5**(1): 61-74.

Menezes, A. C., et al. (2013). "Benchmarking small power energy consumption in office buildings in the United Kingdom: A review of data published in CIBSE Guide F." Building Services Engineering Research and Technology **34**(1): 73-86.

Menezes, A. C., et al. (2014). "Estimating the energy consumption and power demand of small power equipment in office buildings." Energy and Buildings **75**: 199-209.

Metcalf, G. E. and K. A. Hassett (1999). "Measuring the energy savings from home improvement investments: Evidence from monthly billing data." Review of Economics and Statistics **81**(3): 516-528.

Miles, M. B. and A. M. Huberman (1984). "Drawing Valid Meaning from Qualitative Data: Toward a Shared Craft." Educational Researcher **13**(5): 20-30.

Mills, J. E. and D. Treagust (2003). "Engineering Education, Is Problem-Based or Project-Based Learning the Answer." Australasian Journal of Engineering Education **3**(January).

Moorefield, L., et al. (2011). Office Plug Load Field Monitoring Report. California, California Energy Commission, PIER Energy-Related Environmental Research Program.

Mote Jr, C. D., et al. (2016). "The Power of an Idea: The International Impacts of the Grand Challenges for Engineering." Engineering **2**(1): 4-7.

Murphy, L. (2014). "The influence of energy audits on the energy efficiency investments of private owner-occupied households in the Netherlands." Energy Policy **65**(0): 398-407.

NAE (2015). "Grand Challenges for Engineering,." Retrieved July 1, 2015.

NAE (2016). "NAE: National Academy of Engineering." Retrieved September 12, 2016, from https://www.nae.edu/.

Nair, G., et al. (2010). "Factors influencing energy efficiency investments in existing Swedish residential buildings." Energy Policy **38**(6): 2956-2963.

Näsström, G. (2009). "Interpretation of standards with Bloom's revised taxonomy: a comparison of teachers and assessment experts." International Journal of Research & Method in Education **32**(1): 39-51.

Norford, L. K. and S. B. Leeb (1996). "Non-intrusive electrical load monitoring in commercial buildings based on steady-state and transient load-detection algorithms." Energy and Buildings **24**(1): 51-64.

NSBA (2011). "2011 Energy Survey." Retrieved December 20, 2016, from www.nsba.biz/wp-content/uploads/2012/03/2011_energy_survey.pdf.

O'Neill, T. A., et al. (2015). "Life-long learning, conscientious disposition, and longitudinal measures of academic engagement in engineering design teamwork." Learning and Individual Differences **39**: 124-131.

Olsthoorn, M., et al. (2017). "Adoption of Energy Efficiency Measures for Non-residential Buildings: Technological and Organizational Heterogeneity in the Trade, Commerce and Services Sector." Ecological Economics **136**: 240-254.

Oswald Beiler, M. R. and J. C. Evans (2015). "Teaching Sustainability Topics to Attract and Inspire the Next Generation of Civil Engineers." Journal of Professional Issues in Engineering Education & Practice **141**(2): -1.

Ouf, M., et al. (2016). "Analysis of real-time electricity consumption in Canadian school buildings." Energy and Buildings **128**: 530-539.

Palmer, K., et al. (2013). "Assessing the energy-efficiency information gap: results from a survey of home energy auditors." Energy Efficiency **6**(2): 271-292.

Pappas, E., et al. (2013). "Using Bloom’s Taxonomy to teach sustainability in multiple contexts." Journal of Cleaner Production **48**: 54-64.

Pe, J. K. and D. P. Pe (2011). "Update procedures for commercial building energy audits." ASHRAE Transactions **117**(2): 374.

Peet, D. J., et al. (2004). "Integrating SD into engineering courses at the Delft University of Technology: The individual interaction method." International Journal of Sustainability in Higher Education **5**(3): 278-288.

Pellegrini-Masini, G. and C. Leishman (2011). "The role of corporate reputation and employees' values in the uptake of energy efficiency in office buildings." Energy Policy **39**(9): 5409-5419.

Perry, W., et al. (2008). "Grand challenges for engineering." National Academy of Engineering, Washington, DC.

Persson, J. and S. Grönkvist (2015). "Drivers for and barriers to low-energy buildings in Sweden." Journal of Cleaner Production **109**: 296-304.

Pierrakos, O., et al. (2013). An Innovative Two-Year Engineering Design Capstone Experience at James Madison University. 120th ASEE Annual Conference and Exposition. Atlanta, GA.

PNNL (2016, 4/14/2016). "Rooftop Unit Comparison Calculator." Version 4.4. Retrieved May 5, 2017, from http://www.pnnl.gov/uac/.

Popescu, D., et al. (2012). "Impact of energy efficiency measures on the economic value of buildings." Applied Energy **89**(1): 454-463.

Pulvers, K. and G. M. Diekhoff (1999). "The Relationship between Academic Dishonesty and College Classroom Environment." Research in Higher Education **40**(4): 487-498.

Qualtrics (2015). "Qualtrics Survey System." August, 2015. Retrieved May - August, 2015.

Regnier, C. (2014). 2030 District Program and Small Commercial Toolkit. 2014 Building Technologies Office Peer Review, Berkeley Lab.

Revell, K. (2014). "Estimating the environmental impact of home energy visits and extent of behaviour change." Energy Policy **73**: 461-470.

Riley, D. R., et al. (2007). "Teaching sustainability in building design and engineering." Journal of Green Building **2**(1): 175-195.

Riley, D. R., et al. (2012). Process Performance Evaluation of Home Energy Assessment Procedures. Building America NELC-(1)**:** 8-12.

Roberson, J. A., et al. (2002). Energy Use and Power Levels in New Monitors and Personal Computers. Berkeley, CA, Lawrence Berkeley National Laboratory.

Roberts, J. M. (2008). Igniting Inspiration: A Persuasion Manual for Visionaries, Booksurge Publishing.

Robinson, D. and H. Reichmuth (1992). The use of short-term measurements to decompose commercial billing data into primary end uses. 1992 ACEEE Summer Study on Energy Efficiency in Buildings: Achieving Technical Potential: Programs and Technologies That Work. Pacific Grove, CA.

Rohdin, P. and P. Thollander (2006). "Barriers to and driving forces for energy efficiency in the non-energy intensive manufacturing industry in Sweden." Energy **31**(12): 1836-1844.

S. 83 - 100th Congress (1987). National Appliance Energy Conservation Act of 1987.

S. 535 - 114th Congress (2015). Energy Efficiency Improvement Act of 2015.

Sams, A. and J. Bergmann (2013). Flip your students' learning.(student-centered flipped learning). Alexandria, Association for Supervision and Curriculum Development. **70:** 16.

Schleich, J. (2004). "Do energy audits help reduce barriers to energy efficiency? An empirical analysis for Germany." International Journal of Energy Technology and Policy **2**(3): 226-239.

Schleich, J. and E. Gruber (2008). "Beyond case studies: Barriers to energy efficiency in commerce and the services sector." Energy Economics **30**(2): 449-464.

Schultz, P. W., et al. (2015). "Using in-home displays to provide smart meter feedback about household electricity consumption: A randomized control trial comparing kilowatts, cost, and social norms." Energy **90, Part 1**: 351-358.

Shapiro, I. M. (2012). "Energy Audits, Improvements In Small Office Buildings." ASHRAE Journal **54**(10): 14.

Shelton Group and Worldview Thinking (2011). "Full Spectrum Insights: A New Way to Motivate Sustainable Behaviors." Retrieved January, 2011, from http://sheltongrp.com/full-spectrum-insights-combining-sustainability-segments-and-worldviews/.

Shen, Q. and X. Wang (2014). "An analysis of the optimization disaggregation algorithm in the estimation related to energy consumption of appliances in buildings." Applied Mathematics and Computation **234**(0): 506-519.

Shields, D., et al. (2014). "Incorporating sustainability in engineering education." International Journal of Sustainability in Higher Education **15**(4): 390-403.

Somanader, T. (2016). "President Obama: The United States Formally Enters the Paris Agreement." Retrieved September 16, 2016, from https://www.whitehouse.gov/blog/2016/09/03/president-obama-united-states-formally-enters-paris-agreement.

Sorrell, S., et al. (2000). Barriers to Energy Efficiency in Public and Private Organizations. Final Report to DG Research Under the Project 'Barriers to Energy Efficiency in Public and Private Organizations'. SPRU—Science and Technology Policy Research. Brighton, UK, University of Sussex.

Sprehn, K. A., et al. (2013). "Information Format and Cognitive Style: The Impact of Paired Styles on Performance and Preference." Proceedings of the Human Factors and Ergonomics Society Annual Meeting **57**(1): 1129-1133.

Sprehn, K. A., et al. (2015). "Content Analysis of Home Energy Audit Reports: Quantitative Methodology for Standardization." Journal of Architectural Engineering **21**(4).

Steg, L. (2008). "Promoting household energy conservation." Energy Policy **36**(12): 4449-4453.

Stephens, J. C., et al. (2008). "Higher education as a change agent for sustainability in different cultures and contexts." International Journal of Sustainability in Higher Education **9**(3): 317-338.

Stubbs, W. and C. Cocklin (2008). "Teaching sustainability to business students: shifting mindsets." International Journal of Sustainability in Higher Education **9**(3): 206-221.

Sylvestre, P., et al. (2013). "Exploring Faculty Conceptualizations of Sustainability in Higher Education: Cultural Barriers to Organizational Change and Potential Resolutions." Journal of Education for Sustainable Development **7**(2): 223-244.

Tetlow, R. M., et al. (2015). "Identifying behavioural predictors of small power electricity consumption in office buildings." Building and Environment **92**: 75-85.

Timilsina, G. R., et al. (2016). "Understanding energy efficiency barriers in Ukraine: Insights from a survey of commercial and industrial firms." Energy **106**: 203-211.

Tocco, J. and D. Carpenter (2010). Adopting The BOK2: The Quest To Slay The Multi Headed Hydra. 117th ASEE Annual Conference and Exposition. Louisville, Kentucky.

Tocco, J. V. (2014). "Course Enhancement by Melding the BOK2 Student Outcomes with the Project Management Body of Knowledge." 121st ASEE Annual Conference and Exposition: 1-20.

Toto, R. and H. Nguyen (2009). Flipping the work design in an industrial engineering course. 39th Annual Frontiers in Education Conference: Imagining and Engineering Future CSET Education, San Antonio, TX.

Trianni, A. and E. Cagno (2012). "Dealing with barriers to energy efficiency and SMEs: Some empirical evidences." Energy **37**(1): 494-504.

U.S. Census Bureau (2012). "Growth in Urban Population Outpaces Rest of Nation, Census Bureau Reports." Retrieved August 18, 2016, from https://www.census.gov/newsroom/releases/archives/2010_census/cb12-50.html.

U.S. DOE (2013). "Small Buildings = Big Opportunity for Energy Savings." Retrieved December 20, 2016, from www.nrel.gov/docs/fy14osti/60917.pdf.

U.S. DOE (2014). 2014 Smart Grid System Report. Report to Congress.

U.S. DOE (2014). "Energy and cost savings calculators for energy-efficient products." Retrieved January 22, 2015, from http://energy.gov/eere/femp/energy-and-cost-savings-calculators-energy-efficient-products.

U.S. DOE (2015). "The Home Energy Saver™ (HES)." Retrieved January 15, 2015, from www.homeenergysaver.lbl.gov/consumer/.

U.S. DOE (2017). "Building Energy Asset Score." Retrieved May 11, 2017, from http://energy.gov/eere/buildings/building-energy-asset-score.

U.S. EIA (2009). 2009 Residential Energy Consumption Survey. Washington, D.C, U.S. Department of Energy.

U.S. EIA (2012). 2012 Commercial Buildings Energy Consumption Survey (CBECS) Data. Washington, D.C, U.S. Department of Energy.

U.S. EIA (2012). Annual Energy Review 2011. Washington, D.C., U.S. Department of Energy.

U.S. EIA (2017). Annual Energy Outlook 2017 with projections to 2050. Washington, D.C. **January 2017**.

U.S. EPA (2012). "Energy Star® Products 20 years of helping america save energy save money and protect the environment." Retrieved April 14, 2014, from https://www.energystar.gov/ia/products/downloads/ES_Anniv_Book_030712_508compliant_v2.pdf.

U.S. EPA (2016). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2014**:** 558.

van Dijk, H., et al. (2005). A monthly method for calculating energy performance in the context of european building regulations. Ninth International IBPSA Conference, Montréal, Canada.

Vassileva, I., et al. (2012). "Understanding energy consumption behavior for future demand response strategy development." Energy **46**(1): 94-100.

Voytenko, Y., et al. (2016). "Urban living labs for sustainability and low carbon cities in Europe: towards a research agenda." Journal of Cleaner Production.

W.L. Lee, et al. (2003). "A Method to Assess the Energy Performance of Existing Commercial Complexes." Indoor and Built Environment **12**(5): 311-327.

Walberg, H. J. (1972). "Social environment and individual learning: A test of the Bloom model." Journal of Educational Psychology **63**(1): 69-73.

Wang, S., et al. (2012). "Quantitative energy performance assessment methods for existing buildings." Energy and Buildings **55**(0): 873-888.

Wang, T., et al. (2016). "Building energy efficiency for public hospitals and healthcare facilities in China: Barriers and drivers." Energy **103**: 588-597.

Watson, M. K., et al. (2013). Development and Application of a Sustainable Design Rubric to Evaluate Student Abilities to Incorporate Sustainability into Capstone Design Projects. American Society for Engineering Education, Atlanta, GA.

Watson, M. K., et al. (2013). "Assessing curricula contribution to sustainability more holistically: Experiences from the integration of curricula assessment and students' perceptions at the Georgia Institute of Technology." Journal of Cleaner Production **61**: 106-116.

Watson, M. K., et al. (2016). "Assessing impacts of a learning-cycle-based module on students' conceptual sustainability knowledge using concept maps and surveys." Journal of Cleaner Production **133**: 544-556.

WBDG and NIBS (2014). "Whole Building Design Guide." Retrieved January 22, 2015, from www.wbdg.org.

Weatherton, Y. P., et al. (2012). Engineering Sustainable Engineers through the Undergraduate Experience. 119th ASEE Annual Conference and Exposition, June 10 - 13, 2012 San Antonio, TX.

Webber, C. A., et al. (2006). "After-hours power status of office equipment in the USA." Energy **31**(14): 2823-2838.

Weber, L. (1997). "Some reflections on barriers to the efficient use of energy." Energy Policy **25**(10): 833-835.

Wilkins, C. K. and M. H. Hosni (2011). "Plug load design factors." ASHRAE Journal **53**(5): 30-34.

Wilson, C., et al. (2015). "Why do homeowners renovate energy efficiently? Contrasting perspectives and implications for policy." Energy Research & Social Science **7**: 12-22.

Yan, C., et al. (2012). "A simplified energy performance assessment method for existing buildings based on energy bill disaggregation." Energy and Buildings **55**(0): 563-574.

Yona, S., et al. (2008). "Achieving transformative sustainability learning: engaging head, hands and heart." International Journal of Sustainability in Higher Education **9**(1): 68-86.

Yuan, D., et al. (2015). Incorporating Sustainable Engineering Design Principles into Senior Design Proposals. 122nd ASEE Annual Conference and Exposition. Seattle, WA.

Zappe, S., et al. (2009). "Flipping" the classroom to explore active learning in a large undergraduate course.

Zhang, Q., et al. (2012). Challenges for integration of sustainability into engineering education 119th ASEE Annual Conference and Exposition, June 10 - 13, 2012 San Antonio, TX.

Zhao, J., et al. (2014). "Occupant behavior and schedule modeling for building energy simulation through office appliance power consumption data mining." Energy and Buildings **82**: 341-355.

Zilahy, G. and D. Huisingh (2009). "The roles of academia in Regional Sustainability Initiatives." Journal of Cleaner Production **17**(12): 1057-1066.

Zoha, A., et al. (2012). "Non-Intrusive Load Monitoring Approaches for Disaggregated Energy Sensing: A Survey." Sensors (Basel, Switzerland) **12**(12): 16838-16866.