Low-Income Energy Efficiency Programs: A Multicriteria Framework for Energy Audit Software and Evaluation Methodologies for Energy Conservation Measures

A Dissertation Proposal for the

Doctor of Philosophy

Degree

The University of Tennessee, Knoxville

Charles Nii-Baah Amoo

November 2023

Table of Contents

1. Introduction and Review

The impact of buildings on energy consumption and greenhouse gas (GHG) emission cannot be underestimated, yet buildings also offer the greatest opportunity for energy savings and sustainability [1]. Globally, buildings, without including the construction sector, are responsible for 30% of final energy consumption, and 28% of direct and indirect greenhouse gas (GHG) emissions [2], [3], and amounted to a combined $422 billion (about $1,300 per person) in electricity bills to the average consumers in the U.S in 2021 [4]. The International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA) forecast a significant increase in building sector energy consumption [5], [6]. In its 2019 edition of the International Energy Outlook, the U.S. Energy Information Administration (EIA) predicts that energy consumption of all buildings in the world will increase by 1.3% annually between 2018 and 2050. Prior to 2018, building sector energy demand rose by approximately 1.1% per annum between 2000 to 2017, chiefly driven by precipitous increases of floor area of habitable spaces and growing energy intensity of energy services [7]. This increasing trend has implications for the average household, and also for low-income families in the U.S. whose energy burden (that is, the percentage of gross household income that goes into energy bills) is disproportionately higher (8.6%), three times more, than for non-low-income households [8], [9]. In some cases, the energy burden can be as high as 30% when location and income are considered [8], [9].

It seems that global efforts toward energy efficiency are hardly enough to catch up with the rate at which building energy consumption is increasing, as the IEA estimates that efficiency improvements need to reach an average of 4% per year by 2030 if we are to meet global Net Zero Emissions target by 2050 [10]. Meanwhile, residential and commercial buildings form a substantial unserved market for energy efficiency [11]. Yet less than 1% of U.S. buildings are improved each year.

Several agencies in the U.S. are working toward building energy efficiency, especially for low-income households. This includes the Office of State and Community Energy Programs (SCEP) which, among other things, works to accelerate the deployment of clean energy technologies, improve energy efficiency of low-income homes, and reduce the cost of energy associated with such households [12]. Similarly, the Building Technology Office (BTO) is working long-term to reduce the energy use intensity (EUI) of U.S. buildings by 50% compared to the 2010 baseline, and to minimize building EUI in the short-term by 30% by 2030 compared to 2010 baseline [13]. This it intends to do by developing, demonstrating, and accelerating the adoption of affordable technologies, techniques, tools, and services that enable high-performing, energy-efficient residential and commercial buildings in both new and existing markets. This would make all homes and buildings operate at peak energy performance, affordable, and provide optimal health conditions and comfort. On the international front, the IEA proposes that digital products to reduce building sector energy consumption and GHG emissions are outstanding energy efficiency solutions. [14].

In the different goals and objectives of energy efficiency programs, there is the convergence of technology, performance, and affordability at the heart of energy efficiency solutions to meet the needs of low-income households. Meanwhile, there are about 50 million low-income households (44% of households) in the U.S. that may not be able to afford energy efficiency improvements in their homes. Some of the energy efficiency programs being implemented to address these concerns include the Better Buildings Initiative [15], Better Climate Challenge [16] and the Energy Saver [17] programs. However, specific to low-income households is the foundational program of the SCEP, spanning over 40 years – the Weatherization Assistance Program (WAP) – which is the single largest residential whole-house energy efficiency program to reduce energy cost for low-income households in the U.S. through improved energy efficiency [18].

This makes research in energy efficiency solutions for low-income households a subject of grave importance if we are to meet national energy efficiency goals in the U.S. Yet, central to most building energy efficiency programs are energy modeling or energy audit software, but the framework for developing such tools to meet the ever-evolving needs low-income family households are lacking. This study proposes and expands on a framework of criteria that could be used in residential energy audit for low-income households. Energy auditors, energy efficiency program administrators and managers, as well as energy modeling software developers may find it useful in developing, selecting and improving energy audit or modeling software that addresses the energy and non-energy aspects of residential energy audit for users and beneficiaries, while meeting the core goals of energy efficiency. The framework will also provide a qualitative and quantitative description of a list of criteria in the form of a scoring model. With this model, different energy audit software can be assessed to determine their suitability for specific energy efficiency program requirements, or an overall score-based capability of the tool based on an aggregate score of all criteria. This research builds on previous work [19] done by the U.S. Department of Energy (DOE) wherein select energy audit tools were reviewed to support the establishment of a national building performance assessment and rating program.

Another aspect of this research will seek to address how to evaluate energy conservation measure (ECM) lifetimes to develop a repeatable evaluation methodology for ECM lifetimes applied in low-income, residential energy efficiency programs in the U.S. Understanding how to evaluate ECMs lifetimes is of paramount importance, and ensures accurate and reliable evaluation methodologies that can help in effective decision-making, resource allocation, and long-term planning. By including measure lifetime in the study, this research will establish a systematic and standardized approach that can be applied across a diverse range of ECMs, enabling consistent, repeatable, and informed decision-making.

1.1 Brief overview of the energy efficiency challenges in the United States

The greatest challenge facing the building sector is high energy consumption as buildings account for 30% of final energy consumption, [2], and amounted to a combined $422 billion (about $1,300 per person) in electricity bills to the average U.S. consumers in 2021 [4].

Buildings are also a major contributor to greenhouse gas (GHG) emissions, accounting for 28% of direct and indirect emissions [3] (29% in the U.S. [20], with two-thirds of this emission coming from the surging electricity consumption in this sector. Remarkably, since 2000, the rate of electricity consumption in buildings outpaced carbon efficiency efforts of the power sector by a factor of five [21]. Amid the rising carbon footprint of buildings, the IEA notes the important role that technology could play in not only reducing CO_2 emissions but also improving occupant comfort. For example, using heat pumps for heating and solar thermal technologies could cut energy use by a factor of four and provide carbon-free heat to nearly 3 billion people, respectively [21].

The lack of diversification in energy efficiency saving sources is emerging as one of the challenges of energy efficiency facing the residential sector in the U.S. [22]. Traditionally, energy efficiency has focused on known areas of high consumption such as lighting and HVAC, with little attention given to plug-in equipment. Meanwhile, in California, for example, the Natural Resources Defense Council (NRDC) reports that plug-in loads make up only 12 percent of electrical efficiency programs in the state, even though two-thirds of California's residential energy consumption is attributed to plug-in equipment (see Figure 1) [23]. This shows that the rate at which plug-in loads are growing in use in residential buildings is outpacing appliance efficiency standards. Existing energy efficiency programs are not vigorously pursuing and capturing these areas, leaving potential saving areas to go unnoticed [22]. Therefore, energy efficiency efforts should focus on the whole building and all systems that encompass various end-use applications – wherever there is potential to save energy.

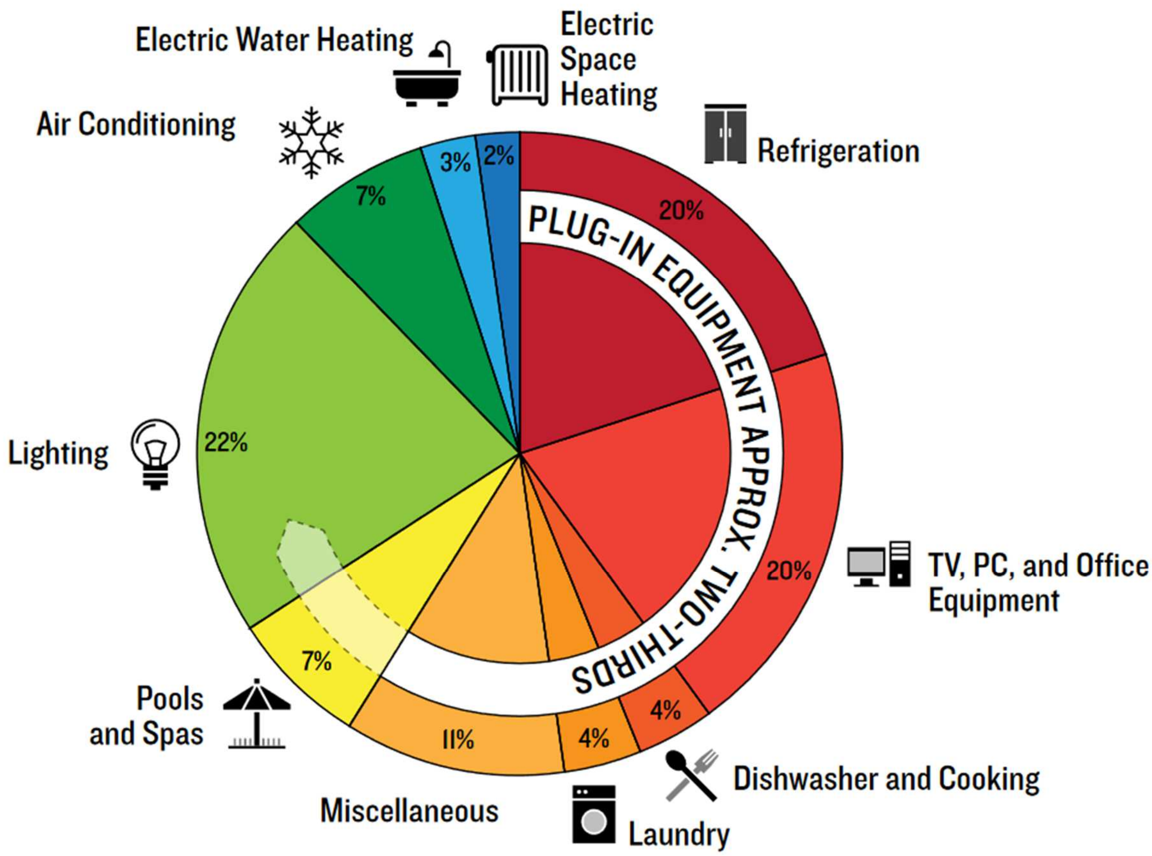

Figure 1: Plug-in equipment responsible for approximately two-thirds of California's residential electricity consumption[1] [23]

Another challenge of energy efficiency is the lack of effort to measure or ensure the persistence or impact of savings. As governments and organizations spend millions of dollars in energy efficiency measures and retrofits, it is important to ensure that estimated energy savings are reliable over the lifetime of installed systems, to meet climate goals and for the purposes of future planning. In the past, the means to measure actual savings, such as the use of smart meters, were lacking and decision makers relied heavily on engineering calculations or estimates from economic analysis. The surge in smart meter data and complex data analytics tools comes with it the ability to monitor changes in building energy consumption or savings as well as observe their significance and persistence across the entire building [24]. Yet, amid recent developments in smart metering technologies to enable real-time monitoring and measurement of energy consumption/savings, little attention is being given to post-retrofit impact of energy efficiency measures. At an MIT Energy Initiative symposium to tackle needed actions to move energy efficiency forward, “big data” was identified to play a key role in tracking energy use and monitoring which energy efficiency efforts are working [25]. This is especially important for energy efficiency programs for low-income households

[1] This chart is focused on electricity. Therefore, it includes only a small share of water and space heating energy, which comes primarily from natural gas in California. Equipment in the Pools and Spas, Lighting, Air Conditioning, and Electric Space Heating categories is mostly hard-wired to the building, but some is plug-in, such as portable electric spas, plug-in lamps, and portable heaters and air conditioners.

funded by taxpayer dollars. There must be a way program administrators can measure post-retrofit savings and other forms of impact.

Affiliated to the lack of effort to measure persistence of savings as described above is the seeming disconnect between building energy efficiency and GHG emissions reduction goals. Building energy efficiency has a crucial role to play in meeting climate goals, yet little connection is made between the two so that it is not clear how meeting the goals of one is helping the other. The goals of energy efficiency must not only be understood in terms of reducing energy cost/consumption of building occupants or operators, but in the broader context of reducing or avoiding GHG emissions [22]. For building occupants or operators who care about positive climate action, this becomes a motivation for collective ownership of organization- or government-led energy efficiency programs to realize greater benefits.

Other areas of concern which this proposal is partly devoted to solving have to do with energy modeling software. In a report by the U.S. Department of Energy summarizing some of the gaps and barriers for implementing residential building energy efficiency strategies, the issues identified regarding energy modeling software include (1) overprediction in older or existing homes, (2) traditional software more tailored to equipment sizing, commercial buildings and new buildings, rather than new and existing residential buildings, and (3) not reliably predicting pre-retrofit energy use and post-retrofit energy savings [26]. Related to all of this is the limited access to energy utility data, further heightened by privacy concerns that make it convenient for utilities to deny utility data requests [26]. While this research will not attempt to solve each individual existing issue with energy modeling software development, especially those applicable to buildings occupied by low-income families, the framework it proposes will provide directions that make solutions possible.

1.2 Problem statement

Meeting the needs of low-income households requires that energy auditors or managers carry out energy audits in accordance with federal or state regulations, using energy audit software or energy modeling tools, and following standard procedures for carrying out energy audits in residential buildings which make up about 95% of U.S. building stock and 70% of total square footage of the building stock [27]. Interestingly, even though U.S. residential buildings are disproportionately higher than commercial (or non-residential) buildings, there has been in existence for more than two decades standard "procedures for commercial energy audit" [28] by the American Society for Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), but none specifically tailored for residential buildings. While the laid-out procedures for commercial building energy audits may be applicable to residential buildings, and the general goal of commercial building energy audits – reduction of energy use and associated cost – may be deemed same for residential buildings, there is more involved in residential building energy audits than just reducing energy use and cost. The variability of residential buildings by type – single-family, multifamily, and mobile homes – and economic levels of building occupants – low-income and non-low-income – require a more nuanced approach to energy audits that sufficiently captures the complexities of different building types or occupants. Besides, carrying out energy audits especially in residential buildings may involve or pose non-energy concerns [29] such as health and safety concerns that need to be captured and addressed within the scope of energy audits. This is especially true for low-income households. All modern energy audits rely on energy audit software or other similar computer programs. However, there is hardly a comprehensive, well-laid-out framework for residential energy audits that energy auditors or energy managers could follow not only in selecting the most-suitable software for these tasks, but also in addressing some of the most pertinent energy- and non-energy-related challenges for both the auditors and the beneficiaries.

Another problem that this proposal seeks to address is the lack of understanding and viable evaluation methodologies for energy conservation measures (ECMs). The evaluation of ECMs and their lifetimes play a crucial role in determining the effectiveness and long-term viability of energy efficiency measures. Most energy modeling software comes with default ECM lifetimes to guide energy auditors in the use of the software for carrying out energy audits. However, ECMs are always evolving in their technology, application and persistence (duration during which they are yielding energy savings). Therefore, energy efficiency program administrators or implementors need to know how to evaluate ECMs, especially their lifetimes. However, there is no repeatable methodology that provides a systematic and standardized approach that can be applied across a diverse range of ECMs to enable consistent, reproducible and informed decision-making.

1.3 Research Significance

The research will contribute to the advancement of knowledge in the field of energy efficiency and provide practical insights for stakeholders involved in low-income energy efficiency programs and policies. Specifically, this research holds immense significance in the following ways and for the following reasons:

- **Mitigating Energy Poverty**: One of the primary drivers behind this research is the urgent need to alleviate energy poverty among low-income households. A comprehensive multicriteria framework for energy audit software selection tailored to their specific needs has the potential to significantly reduce the energy burden on vulnerable households. This, in turn, can lead to improved living conditions, reduced financial stress, and enhanced well-being for millions of individuals and families.
- **A Novel Tool**: By providing a new framework for assessing energy audit software and methodology for evaluating lifetimes of energy conservation measures, energy modeling software developers and energy efficiency program administrators/managers will have a new approach to going about energy audits. Also, decision-makers will be able to better understand and analyze the economic viability of implementing ECMs for a well-informed decision-making process.
- **A Whole Impact Approach:** Traditional energy assessments have often focused on the energy aspects of energy efficiency retrofits. This novel framework also considers the non-energy aspects of energy efficiency not as unintended consequences or benefits, but as deliberate considerations thereby helping to measure the full range of impacts of residential energy efficiency project for low-income households.
- **Measuring and Verifying Impact**: Ensuring the persistence and impact of energy savings is a critical challenge in energy efficiency programs. This study explores the possibility of a repeatable methodology for evaluating energy conservation measures to measure and possibly verify energy savings. By doing so, it ensures the reliability and accountability of energy efficiency efforts, a key aspect of achieving sustainability and demonstrating program effectiveness.
- **Guiding Government Initiatives**: Government agencies and policymakers are investing significant resources in energy efficiency programs for low-income households. This research can provide valuable guidance and evidence-based insights for the design, implementation, and evaluation of such programs. By offering practical solutions and methodologies, it can help government initiatives achieve their energy efficiency and social equity goals more effectively.

1.4 Research Questions

To guide our research efforts, the following research questions will be explored:

- **RQ1:** How can a comprehensive multicriteria framework for energy audit software selection be developed and what criteria should be included to meet the specific needs of low-income households while considering both energy and non-energy factors?
- **RQ2:** How can the developed framework be tested and demonstrated with existing software for residential energy audit to show its strengths and weaknesses?
- **RQ3:** What methodologies can be established to evaluate the lifetimes of energy conservation measures (ECMs) in residential buildings, especially in the context of low-income households, and how can these methodologies be made repeatable and standardized?

1.5 Research Goals

The overarching goal of this research is to develop and demonstrate a comprehensive multicriteria framework for energy audit software, and evaluation methodologies for energy conservation measures that are tailored for low-income energy efficiency programs. To achieve this goal, the following objectives will be met:

Objective 1: Develop a comprehensive framework for residential energy audits that addresses the specific needs and complexities of low-income households, encompassing both energy and non-energy considerations.

Objective 2: Demonstrate how the framework works with existing energy audit software

Objection 3: To establish a systematic and repeatable methodology for assessing the lifetimes of energy conservation measures (ECMs) that can be applied across diverse ECM types, with a focus on their suitability for low-income households.

1.6 Research Scope

This research will primarily focus on low-income households in the United States, recognizing the unique challenges they face in terms of energy efficiency. The scope of the research encompasses the following areas:

- **Residential Building Types**: The research will focus on various types of residential buildings, including single-family homes, multifamily buildings, and mobile homes, to account for the diversity of low-income housing in the U.S.
- **Energy Audit Framework**: The development of a comprehensive energy audit framework will involve the identification of criteria that address energy-related aspects as well as non-energy factors, such as health and safety concerns.
- **Evaluation of Energy Audit Software**: The research will involve the evaluation of energy audit software and energy modeling tools commonly used in the field to assess their suitability for low-income energy efficiency programs.
- **ECM Evaluation Methodology**: A systematic and repeatable methodology for evaluating the lifetimes of energy conservation measures (ECMs) will be developed and tested, with a focus on applicability to various ECM types.

- **Policy and Program Recommendations**: The findings of this research will inform recommendations for policymakers and energy efficiency program administrators to enhance energy efficiency programs targeting low-income households.

1.7 Organization of thesis

- **Chapter 2 will** review literature on energy efficiency programs and their impact on low-income households. It will also review existing methods for evaluating or considerations for developing energy audit software and their limitations. Additionally, a review of existing methodologies for evaluating energy conservation measures will be conducted to understand existing practices.
- **Chapter 3** will present the development of a comprehensive framework for energy audit software, incorporating energy and non-energy factors that consider the needs of both users and beneficiaries. It will also show the methodology for developing the framework and how to use it.
- **Chapter 4** will demonstrate the framework with some existing energy audit software and discuss the findings, showing its strengths and weaknesses.
- **Chapter 5** will present a systematic approach to evaluating ECMs and how they can be applied to diverse ECM types. Also, a repeatable and standardized methodology for evaluating ECMs with long (more than 30 years) lifetime values will be presented.
- **Chapter 6** will summarize the main findings of this research, highlight its unique contributions to current knowledge in the area and make recommendations for further research.

2. Ongoing work

2.1 Developing a Comprehensive Multicriteria Framework for Low-Income Household Energy Audit Software Selection

Research question: *How can a comprehensive multicriteria framework for energy audit software selection be developed and what criteria should be included to meet the specific needs of low-income households while considering both energy and non-energy factors?*

2.1.1 Introduction

In the pursuit of reducing building energy consumption in the United States, the federal government, through the Department of Energy, has initiated, funded, or endorsed numerous building energy efficiency initiatives in various states, spanning both public and private sectors [30]. Researchers from diverse disciplines, including building energy modeling (BEM) and software development, energy-efficient building materials, energy efficient equipment, and energy efficient design, among others, are examining various facets of achieving energy efficiency goals in building environments. This research is one that falls under BEM and BEM software development. Within this field, there exists an underexplored area of research that stands to greatly benefit from further investigation — namely, the development of a comprehensive multicriteria framework to guide the development and assessment of energy audit software suitable for low-income households' energy efficiency. This framework aims to address not only the unique needs of low-income households but also takes into consideration both energy-related and non-energy-related factors.

2.1.1.1 The Energy Audit Process

To delve into and meet the goals of this research, it is important to understand the three steps involved in the entire value chain of an energy audit project – namely, the pre-audit, audit, and post-audit processes [31]. Understanding the steps helps to develop a comprehensive framework that holds relevance in each of the steps. Similarly, a knowledge of three distinct levels of details [32] – Level 1, Level 2 and Level 3 – at which energy audits could be done is an important component of developing the framework. An ASHRAE Level 1 Audit is a preliminary audit that involves identifying no- to low-cost saving opportunities based on a high-level view of potential improvements [32]. In a Level 2 Audit, a more detailed analysis of energy costs, usage and building characteristics is provided which leads to generating Energy Conservation Measures (ECMs) that are based on matching budget against costly potential energy savings opportunities. The Level 3 Audit provides the most thorough of details and includes the most comprehensive financial and engineering analysis of recommendations for which significant capital investment is required [31], [32]. The proposed framework for this research aims at a minimum of Level 2 audit. Related to the levels of detail involved in energy audit is the case of whole-building or tailored audit. An energy audit could be done for a whole building which is the most accurate means of identifying energy savings opportunities in the building, or could be tailored to specific systems such as lighting or heating, ventilation, and air conditioning (HVAC) systems if there is a specific energy efficiency retrofit to be considered. However, the latter could take away from the bigger picture that a whole-building approach can offer [32].

2.1.1.2 The Challenges of Energy Audit

Another aspect of developing a comprehensive framework for energy audit is to understand some of the challenges that energy auditors face in carrying out or implementing the energy conservation measures of an energy audit. [33] highlights ten common problems in energy audits based on a survey of 300 energy audits. According to the survey in [33], one of the leading problems is missed improvements and this happens in about 80% of all audits. The lack of comprehensiveness of audits has often led to not considering or including important measures such as high-efficiency HVAC and HVAC controls, high-efficiency domestic hot water, lighting power density and lighting controls, wall or roof insulation and fenestration improvements [34]. Other top challenges identified in the survey include weak improvement scope, an absence of life-cycle costing and long improvement life (that is, improvements for which the payback is longer than the period for which the installation is anticipated to last). A full list of the ten most common problems and the frequency of their occurrence is shown in Figure 2.

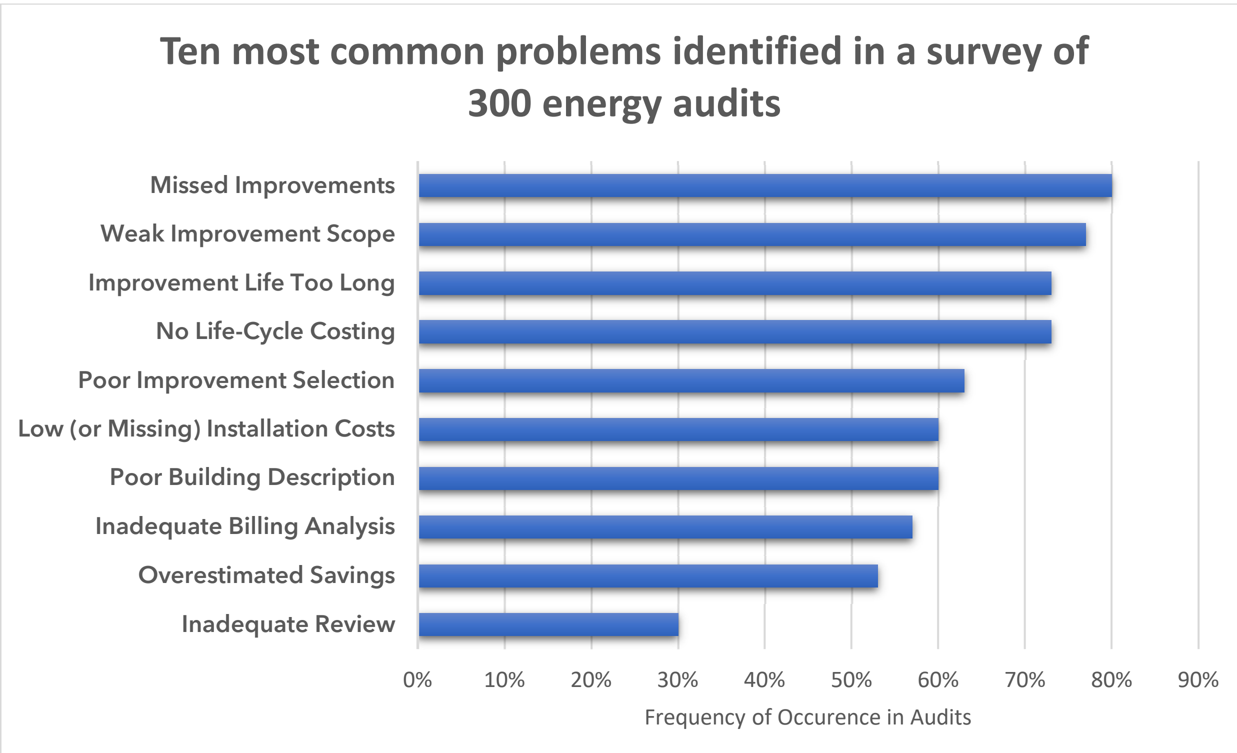

Figure 2: Frequency distribution of the ten most common problems identified in a survey of 300 energy audits [33]

2.1.1.3 The Role of Energy Audit Software

The next step in the framework development process involved establishing the role of energy audit software, not only in performing its core functions of characterizing and analyzing a building's energy usage and providing energy conservation recommendations, but also in addressing some of the top challenges identified in [33] as well as those related to the 3-step process of energy audits and the three levels of AHSRAE energy audits. Already, energy audits software, available as desktop, web- or cloud-based computer programs, are being used to describe buildings, facilities or processes, and measure and analyze their energy use, as well as assist in identifying areas of operation where energy waste can be reduced or eliminated. They provide the advantage of high depth of analysis and rapid delivery of accurate, comprehensive, and cost-effective results or energy efficiency solutions [35]. Energy audit software makes data entry and processing easy by the way data is collected, analyzed and reported. Some energy audit software allow a variety of input methods and data types including utility bills, pictures, building information, and metering and sensor data to create detailed analyses of a facility or process' energy performance [36]. Typically, the engine of an energy audit software is a set of algorithms that combines building physics, local weather data and economic parameters to simulate sophisticated building energy use as well as estimate energy efficiency measures in seconds [37]. It also generates reports that capture distinct aspects of the building's energy use and provides an action-driven, prioritized list of recommendations necessary for implementing energy efficiency retrofits [31]. Energy audit software plays an important role in ensuring that energy auditors are accurate and efficient in their work in a way that reduces error, saves time and is cost-effective. Building owners, facility managers or energy efficiency program administrators can also use the reports of energy audit software to identify cost-saving opportunities and prioritize energy efficiency investments [38].

2.1.1.4 Defining the Criteria for the Framework

Traditional energy audits software appears to have been developed to focus more on the functionality of the software, with important consideration given to aspects such as accuracy, simulation methods (algorithms) and detailed energy analysis and output, among others. While these factors are important, they do not always meet the needs of users and the beneficiaries of the energy conservation measures which the software provides. For the purposes of meeting the goals of this research which focuses on low-income households and considers both energy-related and non-energy-related factors, we propose an expanded framework of a more comprehensive criteria as shown in Figure 3.

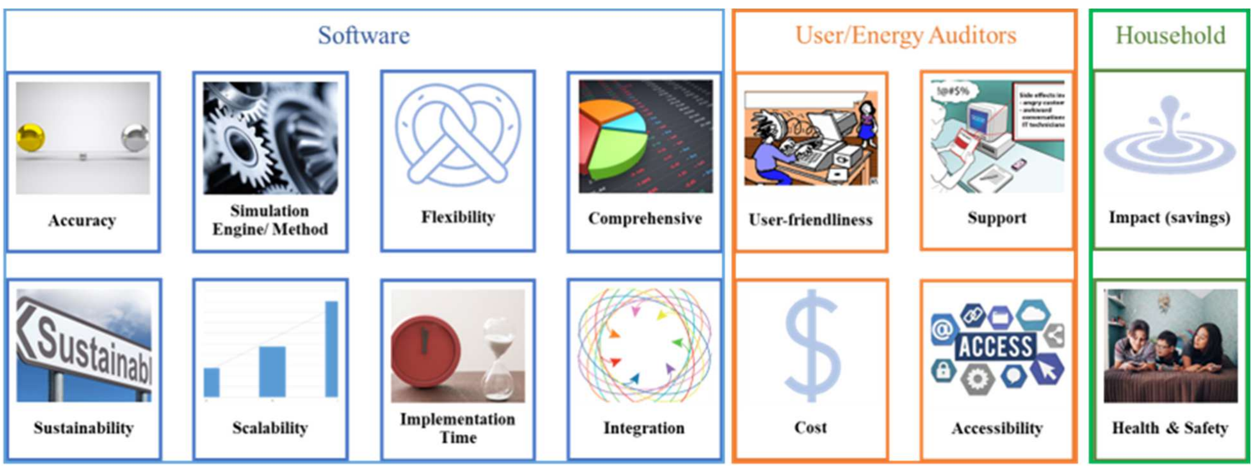

Figure 3: Framework criteria organized into three main groups

The list of criteria that were used to develop this framework may be organized into three main groups, each with a different focus. The first group of criteria focuses on the software tool and ensures that the tool is functional and has the key features that an energy audit software should have. The second group focuses on the user, and guarantees that the software is accessible and useful to those who use it. The last group focuses on the main beneficiaries of the energy audit – low-income households/families – and ensures that their lives are meaningfully impacted by the energy audit.

Each of the criteria of the framework is defined below:

Accuracy: For building energy models generated from simulation based on building descriptors that have underlining or user-defined assumptions, defining accuracy in 'exact' terms may be such a misnomer since all computer-generated models are, at best, close estimates of actual results when validated against measured data. The factors that may influence the accuracy of energy models of energy audit software may include application, scale of application, input data, computational method, calibration and validation methods [39]. In our framework, accuracy will be influenced by building descriptors that apply to residential buildings at the individual building scale, following computational methods that align with proven and acceptable industry standards.

A known and well-established industry standard is the American National Standards Institute (ANSI) and ASHRAE Standard 140 which provides a standard method of test for evaluating building energy modeling (BEM) software [40], [41]. This Standard, which provides a set of test cases and metrics to assess how well a simulation software predicts a building's energy usage compared to actual energy usage, plays a critical role in ensuring that BEM engines give accurate and repeatable test results to developers, energy auditors, energy consultants, energy engineers and other building energy professionals. Even though the ANSI/ASHRAE Standard 140 may be applicable to most elements of residential buildings, it was designed with commercial buildings in mind [42]. Another test procedure more aligned to residential buildings and closely mimicking the test procedures set out in ANSI/ASHRAE Standard 140 is the Building Energy Simulation Test for Existing Homes (BESTEST-EX) [43]. BESTEST-EX leverages either building physics or utility bill calibration to provide test procedures that software developers can use to assess how their energy audit software performs in modeling energy use and savings in existing homes when utility bills are available [43]. BESTEST-EX provides a test suite that represents several cases for both the building physics and calibrated energy savings test procedures. In BESTEST-EX calibration test, an energy modeling or audit software is tested against itself [44], [45]. Also, tested software can be compared with some of the most advanced simulation engines such as EnergyPlus, SUNREL and DOE21-1E[2], a method like ones previously developed by the National Renewable Energy Laboratory (NREL) and included in ANSI/ASHRAE Standard 140 [43]. The different cases evaluate a software's ability to model space heating loads and space cooling loads in representative heating and cooling climates, respectively, for different retrofit options [58]. It also includes combined retrofit cases for both heating and cooling climates together with all the input data for the different cases [47]. A tested energy audit software will be deemed accurate if its simulation results fall within example acceptance range maxima and minima, indicated by 'range' bars. Examples of how the BESTEST-EX tests work are shown in Figure 4 and Figure *5*. Here, the blue and green range bars indicate that the heating tests for gas usage/savings (Figure 4) or cooling test for electricity usage/savings (Figure 5) predicted by testing three energy modeling software – EnergyPlus, Sunrel and DOE2.1 – are within acceptable ranges in 9 different cases.

[2] SUNREL has been retired (no longer in use) and there are more updated versions of EnergyPlus and DOE-2. However, the BESTEST-EX has not seen any major update in more than a decade after its development. Regardless, the procedures employed to develop it are still relevant for modern energy audit software.

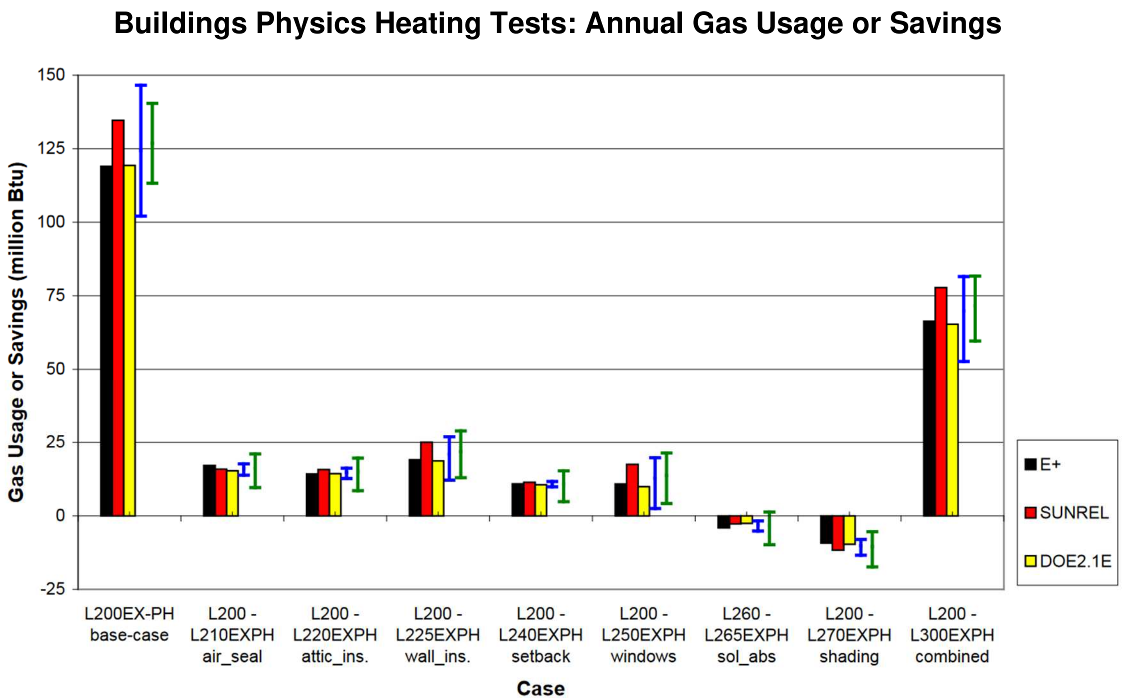

Figure 4 Reference simulation results and acceptance criteria of building physics heating tests[45]

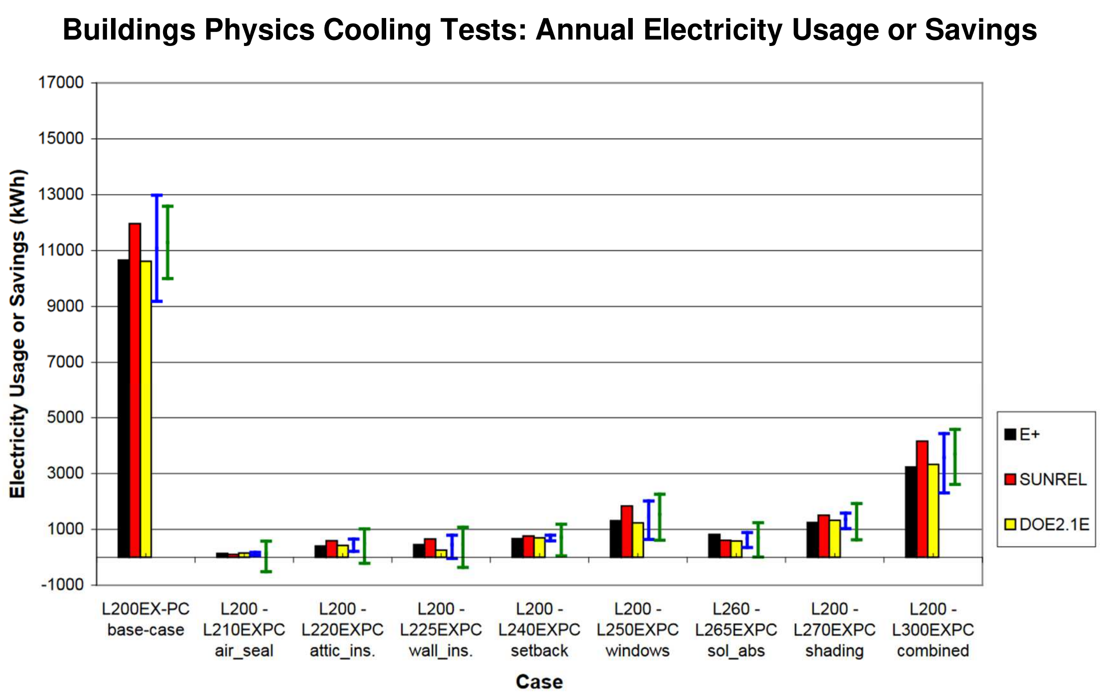

Figure 5 Reference simulation results and acceptance criteria of building physics cooling test [45]

Where the results of a tested software show disagreements with the acceptance range but do not have significant impact on utility cost, that will not be considered enough basis for writing off the tool as inaccurate [47].

Additional procedures to ensure or improve the accuracy of energy modeling software used for energy audits but not discussed within the scope of our proposed framework may be found in [48].

Simulation Method/Engine: In choosing energy audit software, an equally important consideration as the accuracy of the tool is the simulation method that is employed in its development [49]. There are three main approaches to BEM – the physics-based modeling, a semi-physical or hybrid method, and data-driven approach [50]. The physics-based method uses the principles of physics, taking the whole building as a system together with the interactions of all internal subsystems as well as external environmental factors to simulate building energy use [50]. This approach takes input from building descriptors (building geometry, lighting, water heating, HVAC, construction materials, etc.) and building operation/use (occupancy schedules, plug-loads, and controls and sensors) and combines them with local weather data, fuel type and cost, and runs them through physical/mathematical models that could be based on thermodynamics, or mass and energy balance in order to determine thermal loads, system responses and energy use [51]–[53]. Some state-of-the-art physics-based simulation engines with open-source licenses and available for free download include EnergyPlus [54] eQuest, and DOE-2 [55]. Other industry-standard whole-building tools with proprietary simulation engines or EnergyPlus-based simulation engines include Sefaira Systems®, IES Virtual Environment®, TRNSYS®, Pleiades® and Simergy® [56], among others. [50] describes some of the commonly used physics-based software, their modeling process, limitation, advantages and application. While it is acknowledged that developing detailed physical models is an irksome task, [57] notes the higher prediction accuracy of the physical model compared to other simulation methods. This is duly considered in our proposed framework.

The semi-physical or hybrid simulation method uses a first-principle approach to develop physics-based equations to simulate building energy and then uses statistical methods and experimental data to refine the model [58], [59]. The hybrid approach is more computationally efficient than the physics-based approach and is also more flexible and scalable in evaluating energy efficient retrofits in single- or multi-building systems [60]. This method, which provides the advantages and drawbacks of both the physics-based and data-driven approach has been used in assessing energy optimization scenarios to determine the right fit for or balance between HVAC controls or smart-connected systems [58]. The shortcomings of this model, however, which limits its widespread adoption and use include unclear assumption and theoretical limitations, confusing model naming convention and structures, vague model creation and lack of a unified software solution [61].

The data-driven approach is a simple and flexible approach that uses data collected from smart systems and technologies such as smart sensors and electric appliances to improve energy performance using data mining techniques [62]. This approach does not rely on building physics to predict energy behavior [63]. The data-driven approach relies on a history of measured or generated data to reveal mathematical relationships that exist between inputs and output variables using data mining and statistical approaches [64]. This approach has found use in predicting energy use in buildings with complex HVAC controls and building systems connected to them [52].

Flexibility: There is not one software that is designed to address all problems. While software programs are designed to address specific problems, they are not limited to those problems and can often be adapted to address new challenges as they arise. Therefore, minor changes to the problems they were originally designed to solve do not necessarily render the software obsolete or unusable [65]. Flexibility in software engineering relates to the software's ability to continue to function normally despite uncertainty in input values or changes in assumption, goals and processes [66]. A flexible software provides a variety of ways in which the software can be used [67], [68], in addition to being run on different platforms. Software flexibility allows the tool to be customized to fit the specific needs and circumstances of individual cases or scenarios [69]. In our framework, flexibility of an energy audit software would include making the tool customizable and allowing users to input their own data and assumptions, such as the type of HVAC system, the age of the appliances, or the local climate.

Comprehensive: There are diverse types of energy that can be used in buildings. The major energy types are electricity and natural gas, especially in commercial buildings, even though other fuel types such as fossil fuels (coal, natural gas, or fuel oil) and renewable energy sources (photovoltaic technology, bioenergy, geothermal, and wind energy). These energy types could also be used to meet energy needs of buildings that are close together, such as on university campuses or in a city, through a district energy system [70]. Buildings use energy for various purposes, such as lighting, refrigeration, ventilation, space cooling and heating, computer operation, cooking, and water heating, among others [71]. The amount of energy utilized for each application can vary depending on factors such as building type, location, and usage patterns [72]. To improve energy efficiency and reduce costs, building owners and operators should identify and optimize energy consumption for each use [73]. Therefore, it is crucial to have a comprehensive understanding of the ways in which buildings use energy in order to take steps to optimize energy usage for specific use cases. A comprehensive energy audit software, according to our framework, should be able to capture and account for the different fuel types used in a building and how they are used. Figure 6 shows how energy use might be distributed in a residential building by fuel type. Figure 7 and Figure 8 show how energy use in residential buildings might be distributed by their end-use application in percentage and actual energy use, respectively. The ability to capture and the extent to which an energy audit software can account for these variations in energy use determine its comprehensiveness according to our proposed framework.

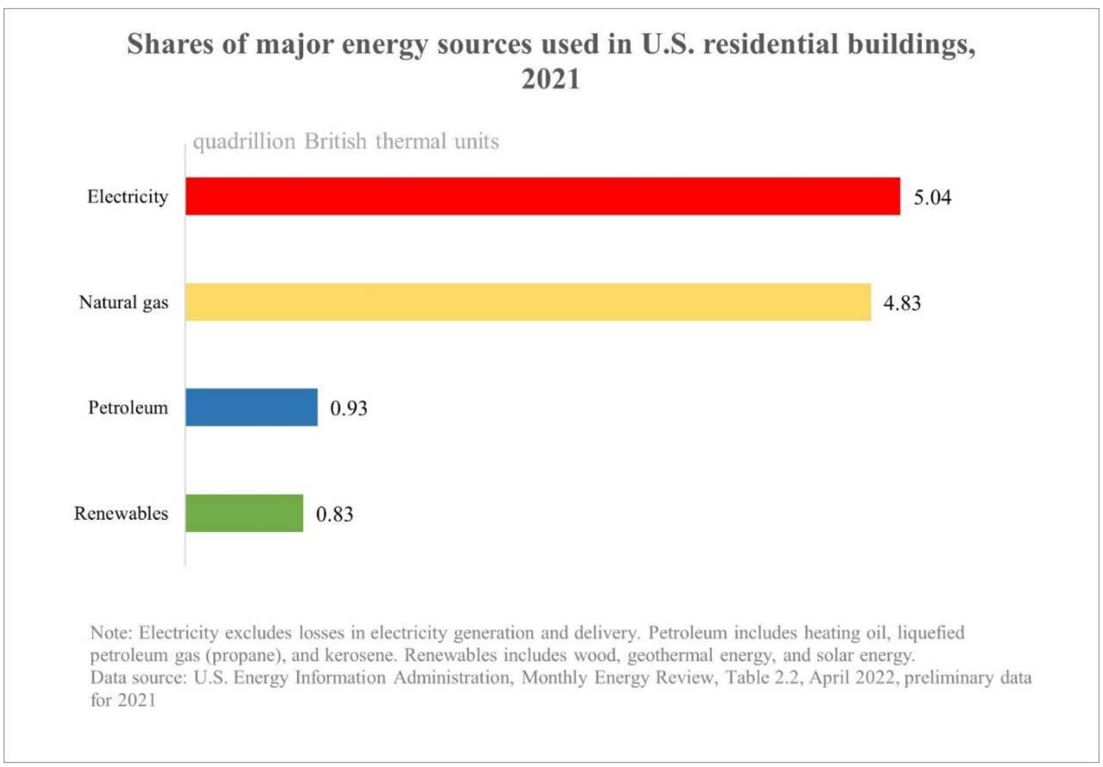

Figure 6 Distribution of energy used in commercial buildings by energy type (2021) [74]

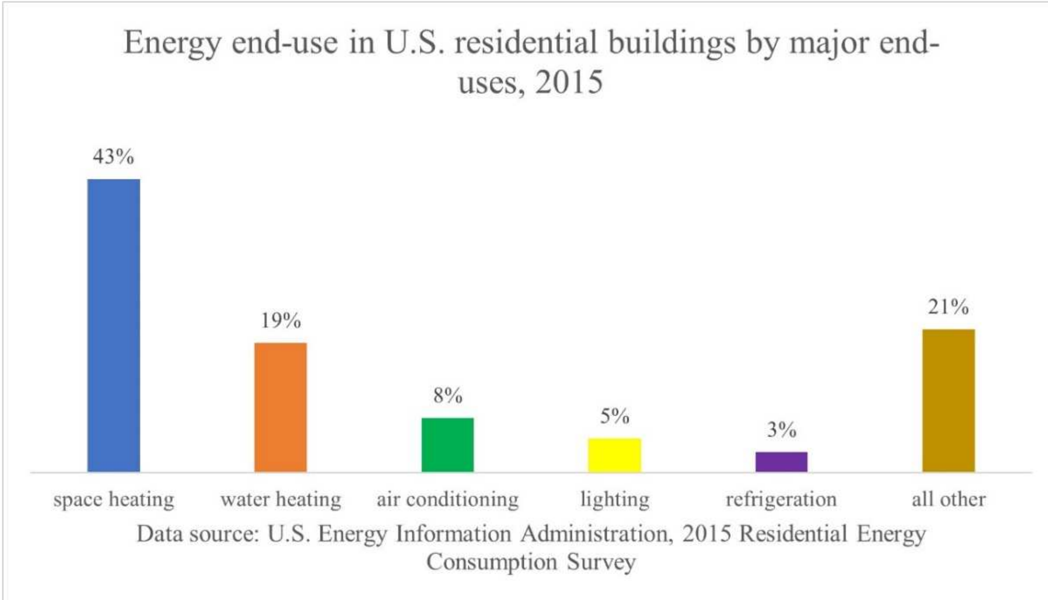

Figure 7 Distribution of electricity end-use in U.S. residential buildings by application (2015) [74]

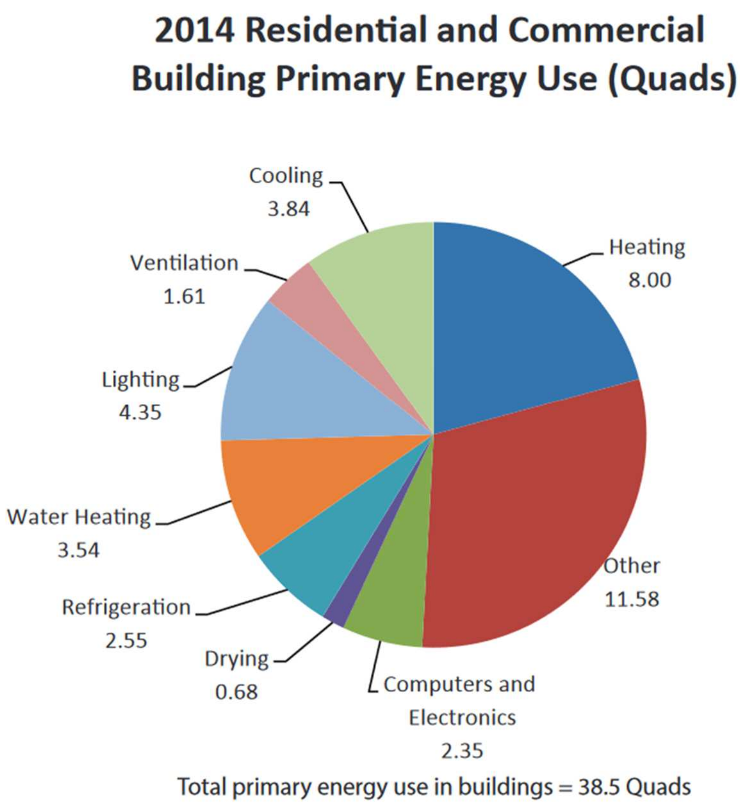

Figure 8 2014 Distribution of primary energy use in residential and commercial buildings [75]

Integration: Integration of software assesses how different software programs could be combined into one system so that the different programs are able to share one database [76]. It is important that software integration allows the different components to communicate with each other to increase efficiency [77]. Some software enable integration on different systems through Application Programming Interfaces (APIs) which can make cross-platform access possible [78]. In our proposed framework energy audit software integration will be assessed by how well the tool integrates with other energy-saving systems, renewable technologies and other programs such as home automation systems and utility rebates – a model that has been proven to lead to significant energy and cost savings [79]. Consequently, our proposed framework recognizes that energy audit software must include such functions.

Scalability: Software scalability determines how the software can withstand expansion in database or increased user activity [80]. It is defined in terms of the software's capacity to adapt to large volumes of work and still be able function at its optimum [81], [82]. In scalability testing, factors that are often considered include response time, that is, the elapsed time between a user's request and the application's response; resource usage – capacity of memory and network bandwidth usage when application is being fully operated; and throughput – the number of requests that can be processed within a given time [83]–[85]. Further scalability metrics are highlighted in [86]. Only an extensive scalability test will be able to address the factors raised [87]. However, for the purpose of our framework, scalability will assess how easily an energy audit software can be expanded to support a larger number of households, and whether it can be used in different geographic locations or run on different hardware and software.

Sustainability: This criterion must not be confused with sustainability in software development which measures the impact of development, deployment and usage of software on the environment, humans, society, and the economy [88], or Green Software System defined in terms of the energy consumption and associated carbon footprint and resource utilization of software use on the environment [89]. According to our framework, this criterion will, however, measure whether the energy audit tool promotes sustainable energy practices and supports the transition to renewable energy sources [90]. This is in line with Title 10 of the U.S. Code of Federal Regulations, Chapter II, Subchapter D, Part 440 (10 CFR 440.1) which establishes the scope and purpose of the weatherization assistance program not only to increase energy efficiency of homes occupied by people in the low-income bracket but also to provide them with renewable energy technologies or systems [91]. Conventional energy audit has focused on efficiency measures to reduce energy consumption and associated cost [92] without exploring how renewable energy technologies such as solar PV systems and solar hot water systems or options could contribute to energy efficiency goals. However, this criterion seeks to reexamine that. Another aspect of this criterion will be to assess how energy use or savings is quantified in terms of GHG emissions [93] contribution or prevention not only in conventional metrics such as tons of CO_2e but in relatable terms such as the emissions contributed or avoided by the equivalent of a certain number of cars, trucks or ships. Furthermore, sustainability as used in our framework will consider the social cost of carbon whereby a dollar estimate is given of the economic cost or damage of what an unabated CO_2 emission into the atmosphere would have been [94]. Providing such metrics could play a significant role in getting individuals and organizations to be motivated to act on such matters which hitherto would have been ignored.

Implementation time: There are about 50 million low-income U.S. households (44% of U.S. households) [95], [96] and about 38.6 million of these households (77.6%) are eligible for weatherization under WAP. Yet, only about 100,000 homes (less than 1% of U.S. buildings) are weatherized each year under the Weatherization Assistance Program [97]. At this rate, it would take approximately 386 years to weatherize the remaining homes that qualify for weatherization assistance. For this reason, implementation time is one of the most important consideration factors in our framework as far as low-income households are concerned. The implementation time includes data acquisition, input, report output and scope generation. Data acquisition is facilitated by an audit checklist that is comprehensive enough to guide the walkthrough and data acquisition phase of an energy audit. An energy audit software should have or generate such a checklist. The implementation time is also enhanced (reduced) by the ease with which gathered data is fed into the software. Input is made easier when the software has clear and concise labeling that makes it easy for users to understand what data is required in each field. Also, the addition of in-built data validation would ensure that the right data type or format is entered to avoid errors. Where the wrong data is input, there should be an inline error message to help users quickly identify and correct such errors. An intuitive and organized user interface would provide users with a clear data flow and make navigation easier. Other factors of easy data input such as keyboard shortcuts, multi-language support, screen optimization and contextual help such as tool tips are important but have been included in a criterion named user-friendliness to avoid redundancy.

After data gathering and input come report output (ECMs) and scope generation. The outputs are related to how fast the computer can process and generate results from local CPU or receive them from remote servers. Here the execution time is considered for desktop applications [98]. The execution time should not be confused with response time as defined under scalability. The execution time of a software refers to the time spent to execute a job that is actively using processor resources [99]. In our framework, we will consider execution time of an energy audit software from when a building that has been characterized is run through the simulation engine to when results are ready. For web- or cloud-based applications, we consider the round-trip time (RRT) instead of the execution time [100]. The RRT measures the duration from when a browser sends a request to a remote server to when a response is received from the server [101]. All these factors, when used together, could determine the implementation time. The importance of the implementation time is that it helps to determine the number of homes that can be analyzed within a specified time. For a fair assessment, it is vital to use one set of building characteristics for all software tools to allow for easy comparison. Regardless, the authors acknowledge that there may be extenuating circumstances which could impact implementation time but have little to do with a tested software's capability or the energy auditor's competence even when the same software is tested iteratively under the same experimental conditions [98].

User-friendliness: User-friendliness in software shows whether the tool is easy to use and understand for users with limited technical expertise. A software's design is informed by its purpose and users. To provide the best user experience, developers must stay connected with the software users [102] through research and feedback. [103] provides a taxonomy of factors to consider for designing applications with user-friendly interfaces and defines them. The relevant factors of [103]'s taxonomy that have been adopted for our framework include speed, ease of use, aesthetic appeal, responsiveness, efficiency and smartness. Others are plugins, security features, error control, update and support.

Support: Software must come with adequate support [104] such as user manuals, customer service, and training materials that address how to install, launch and use the tool [105]. Support must be given through online and offline means [103]. Online support [106] includes Frequently Asked Questions (FAQs) and answers, submitting support tickets, phone communication for technical and business support, online chat, video calls and webinars, remote connection and emails. Offline support could come in the form of "Getting Started" manual, user guide, and training sessions. Responses to requests for support must be prompt and exhaustive to ensure customer satisfaction. Beyond the support that is given by developers to enhance user experience, the requirements of users play a crucial role in software development as user needs are always evolving [107]. Therefore, part of the support should also be tailored to providing a continuous feedback loop whereby users are able to share their experiences and needs [108].

Cost: The criterion of cost in our framework measures the affordability of the tool for users or beneficiaries. Different software would have various pricing models [109]. Regarding energy audit software in the U.S., most of the software that are developed or sponsored by government bodies and agencies are free to download and use. These types of software may be available to the public for both expert and untrained users at no cost. There are other government-agency-approved software that are paid for by government bodies for use by expert users in carrying out agency funded tasks in a Business to Business (B2B) transaction [110]. Other cost models which are explored under this criterion include software licensing [111] with or without maintenance fee, or subscription-based models such as software as a service (SaaS) [112] with options that include metered usage payment, active user counts, or freemium models – that is, free trial for limited period or free version with basic, limited functionalities [113], [114].

Accessibility: An accessible software is one that works for all people regardless of hardware, software, geographic location, language of the user, or physical ability or disability [115]. Our criterion of accessibility would address the concerns of whether, for example, the tool would be accessible to rural households or energy auditors who go to work in remote places with limited internet access or other technological barriers. Also, our definition of accessibility would go beyond having electronic access to the tool and also measures how a person is able to use what is available. For example, if a person has a physical or neuromuscular disorder which poses limitation in fine motor control so that such a person would rather use the keyboard rather than the mouse, will all the functionalities of the software still be accessible from a keyboard [115]? Moreover, does the choice of colors make it easier for those with color-blindness to access the software [116]? Addressing disability concerns should also factor in those with hearing, cognitive, and speech disabilities.

Impact: The impact of an energy audit software, according to our framework, would be measured on whether it is achieving that for which it was built. For other types of software, impact is measured by the number of active users, customer acquisition rate, monthly recurring revenue, customer satisfaction, product engagement or deliverables met [117]. In our framework, the impact of an energy audit software as it relates to low-income households would be ascertained by whether the tool leads to significant energy savings and cost reductions for households. Also, there are non-energy impacts (NEIs) that could be considered such as operations and maintenance savings, occupant comfort, occupant productivity, property value improvement, and lower debt, among others [118]. While NEIs are certainly useful, some are hard to quantify [119] and their immediate benefits may not be ascertained readily as a basis for software selection or scoring. Therefore, NEIs will not be included in our framework except those related to health and safety which are discussed in the criterion named "Health and Safety (Indoor air-quality)."

Health and Safety (Indoor air-quality): This criterion discusses the health and safety aspect of NEI that stems from energy-audit-based retrofit, with focus on the occupant [120]. We consider that energy audit software should provide building occupants with greater control of the building, reduce unwanted temperature variations, and improve the indoor air quality, among others [121]. However, the health and safety aspects of energy audits for building occupants should not come as unintended benefits; an energy audit software should be intentionally designed to address such concerns. This could be implemented by including a checklist that checks for symptoms often associated with building-related health concerns [122]. Additionally, there could also be observation checklists to observe or evaluate the presence of lead, moisture and mold, radon, formaldehyde and volatile organic compounds (VOCs), pest infestation as well as safety hazards, bearing in mind the nature of the occupants – elderly, disabled, children, etc.

2.1.2 Preliminary results

From the framework of 14 criteria is a tabular matrix containing over 50 factors that have been organized under the various criteria. The matrix has been developed to be used qualitatively and quantitatively.

2.1.2.1 Qualitative Framework

A qualitative framework was developed from the definitions given for each criterion. Three- or four-letter code names are assigned to each of the criteria, and the factors and subfactors that are used to measure individual criteria are given in numerical and alphabetical lists, respectively, as shown in Table 1, Table 2 and Table 3. The combination of criteria code names (shown in parentheses on the right of the criteria names) and the numbering of factors and subfactors under them were used to generate unique identities for each of the factors and subfactors of the different criteria. This nomenclature is used in the Quantitative Framework in Table 4, Table 5, and Table 6. For example, ***ACY-2*** (in Table 4) is linked to the second factor under Accuracy in Table 1 (i.e., BESTEST-EX reference simulation results and acceptance criteria), and ***SME-1-B*** (in Table 4) links to a hybrid approach simulation method/engine in Table 1. The difference between the Quantitative Framework and the Quantitative Framework is that the former is without scores while the latter has scores for each of the factors and/or subfactors.

Table 1 Outline of measuring factors in qualitative framework for software-focused criteria.

Software-focused Criteria (Part A)			
Accuracy (ACY)	Simulation Method/ Engine (SME)	Flexibility (FLEX)	Comprehensiveness (COM)
1. Meets ANSI/ASHRAE Standard 140 2. Meets BESTEST-EX reference simulation results and acceptance criteria	1. Simulation Method A. Physics-based B. Hybrid method C. Data-driven 2. Engine A. Known open-source state-of-the-art engine. B. Proprietary	1. Allows customization of data input and assumptions	1. Accounts for different fuel types 2. Accounts for renewable energy resources 3. Provides end-use energy distribution
Software-focused Criteria (Part B)			
Integration (INT)	Scalability (SCAL)	Sustainability (SUS)	Implementation Time (TIME)
1. Integrates with home automation systems. 2. Integrates with utility rebates. 3. Integrates with renewable energy technologies	1. Can support many buildings. 2. Usable in various locations 3. Can be run on different software/ hardware	1. Can explore renewable energy technologies. 2. Quantifies energy usage in terms of GHG emissions/savings. 3. GHS emission/savings metrics are relatable. 4. Provides net-zero energy/emission measures	1. Provides an audit checklist to facilitate data gathering. 2. Clear and concise labeling to help users understand required data input fields. 3. In-built data validation to ensure the right data type and format is entered.

		5. Estimates the social cost of carbon.	4. Inline error message to identify and correct errors 5. Intuitive user interface 6. [3]How long does it take to run a two-story, 3-bedroom, single family home? A. ≤ 10 core-seconds B. > 10 core-seconds 7. [4]What is the RRT for running a two-story, 3-bedroom, single family home? A. ≤ 100 milliseconds B. > 100 milliseconds

Table 2 Outline of measuring factors in qualitative framework for user-focused criteria.

User-focused Criteria			
User-friendliness (USE)	Support (SUP)	Accessibility (ASB)	Cost (COST)
1. Installing and uninstalling was fast and easy. A. Yes B. No C. N/A (for web or cloud-based applications) 2. Application provides keyboard shortcuts. 3. Navigating pages and input fields is possible using the tab key 4. The choice of design colors is appealing and	1. The software comes with a user manual. 2. Training materials (videos and webinars) are provided/available for use of the software. 3. There are emails or online chats or FAQs and answers to help resolve problems	1. Software Availability A. Online mode only B. Offline mode only C. Offline and online modes 2. All software features are available from a keyboard. 3. Features and reports are	1. Software is free to user with full features in a non-B2B transaction 2. Paid software A. Has a limited free-trial version with full features. B. Has free version with limited features with no time restrictions C. Has a limited free-trial

[3] Applicable for desktop applications
[4] Applicable for web-based applications

poses no problem to the eye 5. Font type and size are readable. 6. Icons and shapes are understandable. 7. No issues with viewing the tool on different devices (laptop, tablet, desktop) 8. Running the application does not affect using other activities. 9. It is easier to select items from menus. 10. It is easier to search for information. 11. Could use the application without having to refer to user guide often. 12. The application works well with [external] mouse and keyboard 13. Software does not crash during use. 14. Software comes with regular updates and bug fixes	4. There is a phone number to call for support 5. There is a means to provide feedback to developers	accessible to color-blind persons	version with limited features. D. Has no free trial version

Table 3 Outline of measuring factors in qualitative model for household-focused criteria

Household-focused Criteria	
Impact (savings) (IMP)	Health and Safety (HS)
1. ECMs generated by software lead to energy and cost savings that is A. Significantly lower than predicted (more than 25% less B. Around what was predicted (within 25% margin of error) C. Significantly above what was predicted (more than 25% higher)	1. Software has checklists to inspect general *health hazards* such as mold, moisture, lead, radon, etc. 2. Software helps to inspect safety concerns related to *injury prevention.* *3.* Software checks safety of the *elderly, disabled and children.* 4. Software checks safety related to *structural integrity of building*. 5. Software checks safety related to *fire and electrical safety*

2.1.2.2 A Quantitative Framework

The nomenclature rule for the coding system, as used in the quantitative framework, follows the order XXX-X-X or XXXX-X-X where the first three or four characters represent the criteria names; the character that follows is a number that corresponds exactly to the numbered list of factors under the criteria used in the qualitative framework tables 2 to 4; and the last character, if any, is a letter representing the subfactors in the same matching order. The tables in the qualitative and quantitative frameworks have been developed to match in that Table 4 matches Table 1, Table 5 matches Table 2, and Table 6 matches Table 3. When it comes to the scoring in the quantitative framework, scores are assigned to each factor or subfactor based on how heavy they weigh in assessing the criteria under which they fall. For example, ACY-1 (score of 10) is twice as important a factor in assessing the accuracy of an energy audit software as ACY-2 (score of 5). In other criteria such as comprehensiveness, and health and safety, all factors have equal weights. That is, COM-1 = COM-2 = COM-3 = 5 and HS-1 = HS-2 = HS-3 = HS-4 = HS-5 = 2. The varied factors of a criterion may be summed up to give an aggregate score of each criterion. For example, the factors for assessing scalability and sustainability add up to 13 and 14, respectively. Even though factors are additive in determining the aggregate score of a criterion, the subfactors are not. For example, under simulation method/engine, only one option is possible and may be chosen from SME-1-A, SME-1-B or SME-1-C. The same applies to the subfactors SME-2-A and SME-2-B. Subfactors are non-additive because of the competing objectives or conflicting trade-offs that exist among the options.

Table 4 Binary score model of software-focused criteria

Software-focused Criteria (Part A)							
Accuracy (ACY)		Simulation Method/ Engine (SME)		Flexibility (FLEX)		Comprehensiveness (COM)	
ACY-1	10	SME-1-A	10	FLEX	5	COM-1	5
ACY-2	5	SME-1-B	6			COM-2	5
		SME-1-C	4			COM-3	5
		SME-2-A	3				
		SME-2-B	2				
Software-focused Criteria (Part B)							
Integration (INT)		Scalability (SCAL)		Sustainability (SUS)		Implementation Time (TIME)	
INT-1	3	SCAL-1	5	SUS-1	5	TIME-1	2
INT-2	3	SCAL-2	5	SUS-2	4	TIME-2	3
INT-3	3	SCAL-3	3	SUS-3	3	TIME-3	4
				SUS-4	2	TIME-4	4
				SUS-5	2	TIME-5	3
						TIME-6-A	5
						TIME-6-B	3
						TIME-7-A	5
						TIME-7-B	3

Table 5 Binary score model of user-focused criteria

User- or Energy-Auditor-focused Criteria							
User-friendliness (USE)		Support (SUP)		Accessibility (ASB)		Cost (COST)	
USE-1-A	3	SUP-1	5	ASB-1-A	3	COST-1	5

USE-1-B USE-1-C[5] USE-2 USE-3 USE-4 USE-5 USE-6 USE-7 USE-8 USE-9 USE-10 USE-11 USE-12 USE-13 USE-14	1 - 1 1 2 2 1 3 2 1 1 2 1 2 3	SUP-2 SUP-3 SUP-4	3 4 2	ASB-1-B ASB-1-C ASB-2 ASB-3	2 5 2 2	COST-2-A COST-2-B COST-2-C COST-2-D	4 3 2 1

Table 6 Binary score model household-focused criteria

Household-focused Criteria			
Impact (savings) (IMP)		Health and Safety (HS)	
IMP-1-A IMP-1-B IMP-1-C	5 10 7	HS-1 HS-2 HS-3 HS-4 HS-5	2 2 2 2 2

2.1.2.3 Possible Use Cases of the Model

This model is only a theoretical proposition that is yet to be assessed with actual energy audit software. However, a few use cases may be possible with it. Software developers could apply it to develop new building energy modeling or energy audit software as well as in improving existing software. This could be done by targeting specific criteria of interest where improvement is needed or all the criteria for a truly holistic assessment. Also, energy efficiency agencies and organizations, program managers and certifying bodies could use this framework to determine and approve energy audit software for use in their energy efficiency programs.

2.1.3 Proposal of remaining work

The framework lacks flexibility and the scores for each factor are intended to be used in a binary approach (all-or-nothing) with no provision for partial credit or partial scores, as the factors in the qualitative framework are listed in a way that should be answered in yes/no or true/false responses. There is no room for subjectivity in the scoring model. However, this may not be the case during an actual use or test case. One viable way around this limitation is to use a weighted multicriteria decision analysis (MCDA) for

[5] USE-1 subfactors are only applicable to desktop applications. Therefore, choosing USE-1-C removes all USE-1 factors from consideration in the scoring model.

scoring different software where the aggregate scores of each criterion in our framework are used as weights. Furthermore, the value function method could be used to assign scores to the directly measurable criteria that are quantifiable in known units such as cost in dollar terms. The direct rating method may then be used to score the criteria for which the value function approach is not possible such as health and safety, or accessibility. This helps to convert the model from a binary scoring model to a continuous scoring model, allowing for partial credit or partial scores to be awarded based on the degree of correctness or accuracy of the responses to the factors. This is because a continuous scoring model will accommodate subtleties or nuances in the factors and make room for variability in scoring.

Further work is required in testing the model with different energy audit software. This will be the focus of research question #2 as the framework is used to develop new energy software, assess and improve existing energy audit software, as well as certify software tools for use in energy efficiency programs.

2.2 Testing and Assessing a Framework for Residential Energy Audit with Existing Software: Strengths and Weaknesses

Research question #2: *How can the developed framework be tested and demonstrated with existing software for residential energy audit? What are the strengths and weaknesses of the framework?*

2.2.1 Introduction

The development of a framework for developing and testing energy audit software, though a good first-step, is not the end goal. The framework itself needs to be tested. One way of testing the framework is to do so against sample energy audit software that is available on the market. Selected software must meet set criteria, the most important of which is the ability to characterize and analyze residential buildings energy performance [19]. Any other features or characteristics of the selected software that would constitute their strengths and weakness pertaining to the criteria established in the framework would be determined during the testing.

To select energy audit software for testing our framework, it was important to establish the criteria of our framework and how the selected software would be tested against them. This has been done and discussed under Section 2.1.1. The ability to test a software against our framework also hinges on the availability of the software. For this purpose, we selected only software that were available for free or with free trials for a set period of time, usually 14-30 days. Per this selection criteria, a number of energy analysis software were identified. These include Home Energy Saver (HES) Pro managed by Lawrence Berkeley National Laboratory (LBNL), Home Energy Yardstick by Energy Star®, eQuest®, OptiMiser®, TREAT, EnergyGuage® by the University of Florida's Florida Solar Energy Center (FSEC), REM/Rate™ Desktop by NORESCO LLC, TREAT® by PSD, and the Weatherization Assistant suite of software (NEAT, MHEA and MULTEA) co-developed and managed by the Oak Ridge National Laboratory (ORNL). Out of this list, the final three that were selected for testing were REM/RATE™, TREAT and Weatherization Assistant. This was due to the suitability of these software for assessing the residential building types that low-income families are more likely to occupy – single family, manufactured housing, and multifamily buildings. Our choice of selected software is confirmed by the DOE-approved energy audit tools for use in WAP as provided in the Weatherization Program Notice (WPN 19-4), Attachment 3 [123]. See Table 7.

Table 7: DOE-approved expedited energy audit tools [124]

	SINGLE FAMILY (1-4 UNITS)	MANUFACTURED HOUSING	SMALL MULTIFAMILY (5-24 UNITS, EACH UNIT SEPARATELY HEATED/COOLED)	LARGE MULTIFAMILY (25+ UNITS OR CENTRAL MECHANICAL SYSTEMS)
EA-QUIP	Developer: Association for Energy Affordability (AEA), New York, NY			
	YES	NO	YES	YES
ECOS	Developer: JAI Software, Farmingdale, ME			
	YES	YES	NO	NO
EQUEST	Developer: Lawrence Berkeley National Laboratory (LBNL), Berkeley, CA			
	NO	NO	YES	YES
OPTIMISER	Developer: OptiMiser LLC, Denver, CO			
	YES	YES	NO	NO
REM	Developer: NORESCO, LLC, Boulder, CO			
	YES	YES	YES	YES
TREAT	Developer: Performance Systems Development (PSD), Ithaca, NY			
	YES	YES	YES	YES
WEATHERIZATION ASSISTANT (NEAT, MHEA, AND MULTEA)	Developer: Oak Ridge National Laboratory (ORNL), Oak Ridge, TN			
	NEAT approved	MHEA approved	NEAT and MulTEA approved only for buildings with individually heated and cooled dwelling units	MulTEA approved only for buildings with individually heated and cooled dwelling units
	"YES" means that the audit tool has been previously approved for this housing stock "NO" means that the audit tool has not been previously approved for this housing type or that it is not designed for this housing type			

We acknowledge that there may be other suitable software that meet the selection criteria we used in our final set which were unknown to us at the time of this research. Also, our choice of software used in our test is in no way an endorsement of their utmost suitability for energy analysis or audits. They are simply for research purposes. Also, given the amount of time involved and the extensiveness of the testing anticipated, it was necessary to settle on just a few pieces of software that would best serve our research goals.

2.2.2 Preliminary results

No actual testing has been done yet but the results of the testing may be summarized as a matrix as shown in Table 8. Discussions will also be provided to highlight significant findings that emerge from the testing.

Table 8: Energy Audit Software Assessment Matrix

Criteria	Software A	Software B	Software C
General Information			
Vendor			
Targeted User			
Primary Use			
Availability			
Accuracy			
ANSI/ASHRAE 140 standard			
BESTEST-EX			
Simulation Method/Engine			
Simulation Method			

Simulation Engine			
Flexibility			
Customization			
Assumption			
Comprehensiveness			
Variety of fuel types			
Renewable energy resources			
End-use energy distribution			
Integration			
Home automation systems			
Utility rebates			
Renewable energy technologies			
Scalability			
Supports many buildings			
Multi-location usage			
Runs on different systems			
Sustainability			
Explores RETs			
Quantifies energy in GHG			
Provides relatable GHG metrics			
Provides net-zero measures			
Estimates social cost of carbon			
Implementation time			
Provides audit checklist			
Clear and concise labeling			
Inbuilt data validation			
Inline error message			
Intuitive user interface			
Reference runtime (core-seconds or RRT in milliseconds)			
User-friendliness			
Ease of installation			
Keyboard shortcuts			
Ease of navigation			
Design colors and effect on eyes			
Font readability			
Intuitive icons/shapes			
Device/screen compatibility/responsiveness of application			
Non-interference of application			
Ease of menu selection			
Search function			
Ease of application use			
External hardware compatibility			
Application stability			
Updates and bug fixes			
User support			
User manual			

Training materials			
Online support			
Phone support			
Customer feedback			
Accessibility			
Software availability			
Accessibility of features			
Disability-friendly			
Cost			
Free to user			
Not free but has:			
A. Free-trial with full features			
B. Free version with limited features			
C. Free-trial with limited features			
D. No free-trial version			
Impact (savings)			
Actual savings < predicted (more than 25% less)			
Actual savings close to predicted			
Actual savings > predicted (more than 25% higher)			
Health and Safety			
Health hazard (mold, moisture, lead, etc.) inspection checklist			
Injury prevention checklist			
Safety of elderly, disabled, children			
Structural integrity safety			
Fire and electrical safety			

2.2.3 Proposal of remaining work

The remaining work to be done in this research is the actual testing of the framework by building upon the work done in Section 2.1. Already, three energy audit software have been identified as mentioned in Section 2.2.1. The strengths and weaknesses of these software will be assessed in light of the framework. Conversely, in the process, we hope to also learn the strengths and weaknesses of the framework in assessing these software in order to refine it. Our goal is to populate Table 8 to create a comprehensive and insightful matrix of software assessment to highlight significant findings from the testing process. This matrix will help in quantifying and comparing the strengths and weaknesses of the evaluated software tools.

2.3 Establishing Repeatable and Standardized Methodologies for Evaluating the Lifetimes of Energy Conservation Measures in Low-Income Residential Buildings

Research question: *What methodologies can be established to evaluate the lifetimes of energy conservation measures (ECMs) in residential buildings, especially in the context of low-income households, and how can these methodologies be made repeatable and standardized?*

2.3.1 Introduction

The evaluation of measure lifetimes plays a crucial role in determining the effectiveness and long-term viability of energy efficiency measures. Understanding how long these measures are expected to last is necessary for determining their economic feasibility, whether to go ahead with their implementation, as well as meeting the overall energy efficiency goals.

2.3.1.1 Definition of Measure Lifetime

The lifetime of an energy conservation measure (ECM) or measure lifetime may be defined in terms of its effective useful life (EUL) [125] which is the median length of time that an installed measure is performing its function and yielding energy savings [126]. A simple way to understand the median length of time is to think of it in terms of the time period for which half of the measures of the same kind will remain in use and half would have stopped functioning for a given sample installations. However, it is important to note that this definition may not fully capture the nuances associated with certain types of measures, such as building envelope measures.

For these types of measures, the measure lifetime concept can become more complex, as it depends on various factors, including the condition of the existing infrastructure, the quality of the retrofit installation, and evolving technology standards. Retrofits may have varying lifetimes depending on these factors and may not always align with the traditional EUL concept.

EUL has two components – the technical life and the measure persistence. The technical life refers to the average length of time that the measure is operational [126]. It is based on engineering tests under standard operating conditions. Therefore, any unfavorable condition or unrecommended use of the measure such as those related to climate, maintenance and installation could affect its technical life [127]. Measure persistence measures the actual time that the measure lasts when factors such as home turnover, early retirement of installed equipment, or retrofits and remodeling, are considered [125], [127].

2.3.1.2 Review of Established Measure Lifetime Methodologies

Literature provides different sources and methodologies for measure lifetimes. However, there is no one established methodology that has been used authoritatively in estimating measure lifetimes. The sources for lifetime estimates range from complex statistical or probability tools such as survival studies to interviews and assumptions. Measure lifetime data sources could also come from manufacturer's warranty, industry standards, field survey, and laboratory tests such as accelerated aging tests. Computer modeling and simulation, as well as expert judgement have also been used. These methodologies are often interrelated in that a measure lifetime from one source/methodology can be used to generate a more realistic or reliable lifetime data based on another methodology. For example, lifetime values from field surveys could be based on expert judgement, survival studies could be based on manufacturer data and field surveys, and expert judgement could be based on assumptions and/or industry standard.

A few of the often-cited sources and methodologies for ECM lifetimes are detailed below:

Survival Studies

Survival studies is one of several statistical methods that may be used to estimate the expected lifetime of events (measures) [128]. However, they are the most common statistical approach used in lifetime estimation. Survival studies can be a source of primary data or secondary data depending on whether researchers generate new insight from existing data or use published survival studies in their research.

Survival studies are a form of stochastic model based on probability theory and statistical methods that model the relationship between given inputs and outputs using mathematical functions that best fit the given data [129]. Generally, survival studies are used to estimate the remaining useful life (RUL) of an event (equipment or installation). It has application in many fields such in the insurance industry for estimating when a claim might be expected or when a policy might become invalid, in asset management for estimating depreciation and value of an asset, or in engineering for estimating the reliability of an equipment or installation to know when maintenance or replacement might be due. As with most statistical methods, survival studies are data-driven and rely heavily not only on the availability of data, but also the nature of the data [130].

Survival studies offer several advantages, and one notable benefit is the utilization of parametric models, such as Weibull Distributions. A parametric model is a type of statistical model for which one defines the distribution of probability variables and makes inferences or assumptions about the parameters of the distribution or form of the data being analyzed [133]. These assumptions, expressed in terms of parameters, are numerical values that define various characteristics of the distribution. In parametric modeling, it is assumed that the data follows a known probability distribution with specific parameter values.

Parametric models exhibit high efficiency and flexibility, making them particularly valuable tools in survival analysis. Unlike some other statistical methods, parametric models can be effectively applied even when dealing with relatively small sample sizes, which is advantageous in situations where obtaining large samples may be impractical or costly [131].

However, it is important to note that while parametric models provide these advantages, they also come with a significant challenge. The primary challenge lies in the selection of the most appropriate distribution for modeling survival data accurately. The choice of distribution is critical because an incorrect or poorly fitting distribution can lead to misleading inferences and results. Factors such as the shape of the data and the underlying assumptions of the chosen distribution must be carefully considered to ensure that the model aligns with the characteristics of the observed survival times [132].

Survival studies can be applied to the design of various engineering and reliability testing of different groups of manufactured items, using different types or nature of lifetime data. [134] used national survey data such as manufacturer data on historical shipment of appliances to US homes and in-use appliances in stock, obtained from the U.S. Energy Information Agency's (EIA) Residential Energy Consumption Survey (RECS 1990, 1993, 1997, 2001, 2005) and the Census Bureau's American Housing Survey (AHS 1991, 1993, 1995, 1997, 1999, 2001, 2003,2005, 2007) to estimate the lifetimes of residential appliances - central air-conditioners, heat pumps, furnaces, boilers, water heaters, room air-conditioners (RACs), refrigerators, and freezers. The U.S. Department of Energy (DOE) has utilized this methodology in measure lifetime estimation as referenced in several its technical support documents (TSDs) on various appliances.

Manufacturer's Data

Manufacturers' data are often based on life test data and assume that the minimum design life of a component should be the same as the useful life of the product [135]. The failure rates of the components of a product can be used to determine the critical lifetime prediction design parameters and, subsequently, to provide warranty or guarantee on products or components of products [135].

Manufacturers' data may provide useful information on how long a product may last (technical life as defined under Definition of Measure Lifetime) or the mean-time-between-failure (MTBF), but they don't always reflect actual use cases.

While there are not many direct uses of manufacturer data solely for measure lifetime estimation, there are many cases of manufacturer data being used, as starting points, with other techniques or methodologies such as in survival functions or clustering analysis or data regression, for more reliable lifetime estimates. For example, research publications on appliance lifetime estimate by the Lawrence Berkeley National Laboratory – LBNL [134] and TSDs by the U.S. Department of Energy [136] relied on manufacturer data.

Industry Standard

Industry Standard refers to data provided by stakeholder groups or professional organizations with expertise, interest or business dealings in specific industries. The DOE defines industry standard as the generally accepted requirements followed by the members of an industry [137]. Developing industry standards often follow a rigorous, orderly and systematic process because these standards serve as a quality check or reference point for professionals to follow in decision-making. There are numerous U.S. organizations developing standards but a few of them that are relevant to this study include the following:

- American National Standards Institute (ANSI): ANSI serves as an administrator and coordinator of U.S. private sectors standardization system which does not develop standards per se but assesses and approves standards developed by others [138].

- The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE): ASHRAE develops standards focused on building systems, energy efficiency, indoor air quality, refrigeration and sustainability within the HVAC&R industry [139].

- The National Institute of Standards and Technology (NIST): NIST is a part of the U.S. Department of Commerce and provides support for the development and use of standards [140].

The use of industry standards for measure lifetime has many advantages. As in any other industry, using industry standards can help save time, reduce costs and increase productivity. It also provides a basis for regulation within an industry and promotes transparency and consistency [141].

Industry standards have frequently served as valuable sources of secondary information in numerous measure lifetimes studies. A notable source of industry measure lifetimes data is from ASHRAE, especially for HVAC units, that is, the ASHRAE HVAC Service Life Database and the ASHRAE Handbook – HVAC Applications [142]. Measure lifetime information from non-standardization bodies have also been utilized in the past including those from trade organizations such as Air-Conditioning, Heating, and Refrigeration Institute (AHRI, formerly ACHRI) and the National Association of Home Builders (NAHB).

Field Survey/Testing

Field survey or testing involves collecting information regarding the actual use and performance of an equipment or installation that can be generalized to infer or represent its use/performance in other or similar situations. Field surveys are one of the means used to collect primary data when secondary data is insufficient or nonexistent [143]. Field survey data can be gathered through personal interviews or survey instrument (questionnaire), as well as in-person or remotely when the former is inconvenient or unsuitable. In addition to interviews and survey instrument, field surveys could include a review and analysis of historical data to determine how long measures have lasted under certain operating conditions, but this approach would require access to and analysis of a large database of performance or lifetime data to ensure that valid conclusions are drawn.

One advantage that field surveys have is the human interaction involved [143]. If done in-person rather than remotely (video or phone surveys), it has the added advantage of adding context to data such as user behavior regarding use of the measure, how measure was installed, or condition of use, through firsthand observation, all of which improve the quality of the data gathered. A disadvantage, however, is that field surveys can be expensive and time-consuming as they could take years to complete. It is also possible to introduce researcher bias in the survey data.

Many of the measure lifetime reports on energy efficiency retrofits have involved conducting field surveys as part of monitoring and evaluation of the performance of energy efficiency programs. A few examples are found in [144] and [145].

Accelerated Aging Test

Accelerated aging test, also known as accelerated life test (ALT) involves using different methods to shorten the life of a product by accelerating its age through degradation. This is done in order to obtain in a quick manner the data needed to analyze the product's life under standard operation. To do this, the product is subjected to stress under different levels and times – in increasing order – until failure is achieved or a censoring time is reached [146].

A drawback of this method is the introduction of censoring in the data collection. In an ATL experiment of manufactured items, for example, it may not be possible to observe the failure of all items under observation and the observation may need to be terminated before the complete failure of all events, leading to a possible underestimation of the failure time [146]. This early termination is often a practical necessity due to time and resource constraints. Consequently, some products in the study may not have failed by the end of the experiment, leading to a situation known as "censoring." Censoring simply means that the exact failure times of these items remain unknown. Therefore, statistical methods that account for censored data, such as survival analysis, may be used to estimate the product's lifetime distribution.

This methodology has been widely applied in determining the reliability and lifetime characteristics of various manufactured products, including mechanical and electronic components [147].

Modeling and Simulation

Modeling and simulation are data-driven approaches that use large datasets to identify relationships in the datasets in order to predict future outcomes. Modeling and simulation may utilize various clustering techniques or different regression models to predict the lifetime of equipment. Datasets that are used for this type of modeling may come from manufacturer data on warranty or guarantee times, Mean-Time-To-Failure (MTTF) or Mean-Time-Between-Failure (MTBF) of a Weibull analysis and time-to-failure data [135]. Where historical data is missing or insufficient, a Monte Carlo Simulation can be used to fill in the data gaps.

As with all data-driven models, the modeling and simulation approach to measure lifetime estimation may be highly efficient and inspire more confidence in the prediction values. However, they require large datasets which are difficult to gather. Not only so, but the data that are used in the training set must come from different contexts to represent the unique conditions of use in each of the contexts where the predicted lifetimes values will be applied in actuality and applicable to a wide range of use cases. Furthermore, to ensure robust predictions applicable across various contexts, the data used in the training set must encompass a range of conditions, mirroring the diversity of real-world scenarios where predicted lifetime values will be employed. Otherwise, the models will have a reduced prediction accuracy [148]. Furthermore, lifetime value predictions are only dependable to the extent that the models used are the appropriate ones.

Data-driven modeling and simulation have been applied to predict the remaining useful life of rolling bearings [149], lithium-ion batteries [150] and to predict tool wear [151] (Wu, et al., 2017).

Expert Judgement

Expert judgement may be defined in terms of data given by an expert in response to a technical problem. The expert, in this case, must have background in the subject area and must be recognized by one's peers or those seeking answers that the expert has the qualifications, experience and credibility to be right or about right in the answers given [152].

When estimating measure lifetimes, expert judgement may play a vital role where test results are limited, dubious, or nonexistent. For example, expert judgement could be useful in providing estimates on new measure lifetime or poorly understood measures, forecast future events, integrate or interpret existing measure lifetimes, and in filling knowledge gaps [152]. Expert judgment may be elicited through individual interviews, interactive groups and Delphi technique (in isolation from one another) [152].

Expert judgement comes in handy when there are not many viable options to explore measure lifetimes and expert judgement may be the only or one of few alternatives to pursue. However, studies have shown that expert judgement may have certain pitfalls such as the introduction of bias in data through misinterpretation or misrepresentation, limitations in the number of things that experts can mentally juggle, as well as the level of detail in the data [152]

Expert judgement has often been utilized in literature, including weatherization studies, to estimate measure lifetimes. These include those authored by DOE and its offices/agencies, US national laboratories, independent consulting firms such as Navigant, and labor organizations and associations.

Table 9: Historical lifetime values from Weatherization Program Notices and Weatherization Assistance Libraries

#	Measure Type	Measure Name	WPN-23-06 (Eff.3/3/23) Life (yr.)	WPN-19-4 (Eff. 1/17/19) Life (yr)	WA User Manual v8.9 (2015)	NEAT/MHEA User Manual v.7 (2002)	NEAT User Manual (1997)	NEAT User v5.2 (1996)
1	Building Insulation	Attic insulation: blown in and batt	30	30	20	20	20	20
2		Attic insulation: all other types	20	20	20	20	20	20
3		Sillbox insulation	20	20	20	15	15	15
4		Foundation wall insulation	20	20	20	20	20	20
5		Slab insulation	20	20				
6		Floor insulation: loose and batt types installed in fullyenclosed air-tight cavities, and rigid insulation	30	30	20	20	20	20
7		Floor insulation: all other types including loose and batt, not installed in fully enclosed air-tight cavities	20	20	20			
8		Wall insulation: dense pack insulation, rigid insulation and full-cavity batt insulation in fully enclosed air-tightcavities	30	30	20	20	20	20
9		Wall insulation: all other types	20	20	20			20
10		Kneewall insulation: loose and batt types installed infully enclosed air-tight cavities, and rigid insulation	30	30	20	20	20	20

11		Kneewall insulation: all other types including loose and batt types not installed in fully enclosed air-tight cavities	20	20	20			
12		Duct insulation	20	20	20	20	20	20
13		Manufactured home skirting	10	10	10	10 (MHEA)		
14		White roof coating	7	7	7 (NEAT), 20 (MHEA addition)	20 (MHEA)		
15		Radiant barrier	15	15				
16	Ducts/ Infiltration	Whole house air sealing	10	10	10 (MHEA)	20 (MHEA)		
17		Duct sealing	10	10	10 (MHEA)	10 (MHEA)		
18	Doors and Windows	Storm window	15	15	15 (NEAT; Glass storm window in MHEA), 5 (Plastic storm window in MHEA)	15	15	15
19		Window replacement	20	20	20	20 (Double pane), 15 (Low-e)	15 (low-e)	15
20		Door replacement	20	20	15 (MHEA)	15 (MHEA)		
21		Storm door	10	10	10 (MHEA)	10 (MHEA)		
22		Window shading: awning	10	10	10 (NEAT/MHEA), 15	10	10	10

					(MHEA addition)			
23		Sunscreen: fabric or screen	10	10	10	12	12	12
24		Sunscreen: louvered	15	15	15	20	20	20
25		Window film	15	15	15	5	5	5
26	HVAC Systems	Thermal vent damper	10	10	10	10	10	10
27		Electric vent damper	10	10	10	10	10	10
28		Intermittent Ignition Device (IID)	10	10	10	10	10	10
29		Electric vent damper and IID	10	10	10	9	9	9
30		Flame retention burner	10	10	10	10	10	10
31		Heating system tune up	3	3	3	2	2	2
32		Heating system replacement: fossil fuel fired furnaces and, boiler standard and condensing	20	20	15 (High efficiency furnace & boiler)	15	15	15
33		Heating system replacement: all other heating systemsexcept heat pumps	18	18	18	15	15	15
34		Smart/programmable thermostat	15	15	15	15	15	15
35		Air conditioner tune up	3	3	3	5	5	
36		Air conditioner replacement	15	15	15	15	15	15
37		Evaporative cooler	15	15	15	15	15	15
38		Heat pump replacement	15	15	15	15	15	

39	Baseloads	Lighting retrofit: fluorescent and compact fluorescent	(10,000 hours)	(10,000 hours)	10	10	10	
40		Lighting retrofit: LED	(30,000 hours)	(30,000 hours)				
41		Lighting retrofit: halogen	(4,000 hours)	(4,000 hours)				
42		Refrigerator replacement	15	15	15			
43		Water heater tank insulation	13	13	13	10 (NEAT), 15 (MHEA)		
44		Water heater pipe insulation	13	13	13	15		
45		Low flow showerhead	15	15	15	15		
46		Water heater replacement	13	13	13			
47		Water heater setpoint reduction	13	13				
48	Solar	Solar PV installations	20	-				

2.3.2 Preliminary results

Preliminary results demonstrate practical ways of obtaining or determining the lifetime of different categories of energy retrofit measures in a manner that can be replicated. These include Product Category Rule (PCR) and Environmental Product Declaration (EPD) documents, and ASHRAE service life and maintenance cost database. The results also show how to address conflicting lifetime values for the same measure and explain the various factors that may affect the service life of ECMs.

2.3.2.1 Obtaining Reference Service Life (RSL) from Product Category Rule (PCR) and Environmental Product Declaration (EPD)

The Reference Service Life (RSL) refers to the duration for which a product remains in use [153]. RSL data may be obtained from different sources, including the Product Category Rules (PCRs) and Environmental Product Declaration (EPD) documents, which are valuable tools for estimating the lifetime of ECMs. The Product Category Rule (PCR) serves as the foundation for generating an Environmental Product Declaration (EPD). The PCR outlines the guidelines for conducting a life cycle assessment (LCA) of a product [154]. EPDs, on the other hand, offer credible environmental performance data for various products – building materials, consumer goods, electronic devices, vehicles, and many others – aligning with international standards like ISO 21930 [155] and EN 15804 [154], [156].

It is important to note that RSL values may vary depending on the data source, with factors such as indoor and outdoor environments, product design, and predicted maintenance playing a role [157]–[159]. To estimate the RSL of a building component, three main approaches are recognized [157]. The first approach is rooted in engineering principles, focusing on the structural integrity and material fatigue over time. The second approach considers various factors such as component quality, design level, work execution, and environmental conditions to modify the RSL for an estimate. The third approach relies on empirical data, which, while accurate, can be resource-intensive to obtain.

In addition to individual EPDs, other data sources for obtaining RSL include client requirements, manufacturer information, applicable standards (e.g., ISO 15686-1, -2, -7, and -8), national service life databases, LCA software, and professional organizations [153]. Research group publications, initiatives, and scientific publications also serve as valuable sources for RSL data for building components and products.

To find the RSL of a product from an EPD, one may use the following steps:

Step 1: Search the EPD library at https://www.environdec.com/library. The EPD and PCR library can be located at the top right of the menu bar.

Step 2: To search for a product type such as insulation, type “insulation” in the input field of Filter to show the most recent EPDs on insulation available in the library.

Step 3: One can also filter the search by product category such as chemical products, construction products, infrastructure and building, machinery and equipment, and others; or by PCR which provides a finer breakdown of the options in the Product Category field. The Geographical scope options filters the search by country, region or continent, while the validity filter allows users to choose the periods within which EPDs ought to be valid.

ECM Lifetime Evaluation from Public Database

The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) maintains a public database that provides current information on service life and maintenance cost of all major pieces of HVAC equipment and be accessed at http://weblegacy.ashrae.org/publicdatabase/service_life.asp

Users may access the database by following the steps below:

Step 1: Visit the ASHRAE HVAC Service Life Database [160] to access the ASHRAE service life database.

Step 2: Use the service life data query in Step 1 to customize your search from the database by filtering through equipment by system type (air distribution, cooling, heat rejection, cooling pump, heating, heating pump, control, miscellaneous), region, state, function of building where HVAC equipment is intended to be used, size of building, height of building or number of stories, Building Owner and Managers Association (BOMA) classification, and location.

The database allows users to search for equipment service life data by building type or function. This can be found by clicking on "Function" to expand the field and then scrolling through the options to select the desired building type or function as shown in Figure 13. An obvious limitation of this database, however, is that it is more focused on commercial buildings and has limited residential building types.

2.3.2.2 Dealing With ECMs with Long Lifetime Values

Each year, the National Institute of Standards and Technology (NIST) publishes an annual supplement to the NIST Handbook 135 named Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis. At the time of this report, the most recent one was for 2022 with document ID: NIST 85-3273-37 [161]. This document is a life-cycle cost manual for the Federal Energy Management Program (FEMP) that provides energy price indices and discount factors for use with the FEMP procedures for life-cycle cost analysis and can be used to evaluate potential energy and water conservation and renewable energy investment in existing and new buildings. The price indices and discount factors in this document are estimated using the most recent energy price projections from DOE's Energy Information Administration (EIA) Annual Energy Outlook and the Office of Management and Budget (OMB).

The maximum allowable ECM lifetime in WAP is usually consistent with the maximum projection year in the NIST Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis report, which is 30 years at the time of this publication, as has been for a few years. Some EPD and lifetime data sources for insulation materials and other building envelope measures provide service life information that are reasonably long – 50 years – and are projected to last, in some case, as long as the buildings in which they are installed. Since no ECM lifetime in WAP can be longer than the life-cycle cost analysis period given in NIST, ECMs such as certain types of building insulations that are deemed to have useful service lives longer than 30 years or current NIST projection period, whichever is longer at the time of review, shall be guided by information in current NIST publication rather than what other sources provide.

2.3.2.3 Addressing Varied Lifetime Values for The Same Measure

In instances where diverse sources of data yield differing lifetime values for a particular appliance, the need often arises to establish a single, representative value for that measure. To achieve this, various statistical techniques can be employed. Among these techniques, the Weibull Distribution stands out as a proven and efficient method, characterized by its adaptability and suitability for situations involving limited sample sizes [131].

A comprehensive study conducted by Lawrence Berkeley National Laboratory (LBNL) exemplifies the application of this approach. The study drew upon national survey data, including historical appliance shipment records and in-use appliance data obtained from the Energy Information Agency's (EIA)

Residential Energy Consumption Survey (RECS) spanning multiple years (1990, 1993, 1997, 2001, 2005), as well as data from the Census Bureau's American Housing Survey (AHS) across various years (1991, 1993, 1995, 1997, 1999, 2001, 2003, 2005, 2007). This extensive dataset facilitated the estimation of lifetimes for various residential appliances, including central air-conditioners, heat pumps, furnaces, boilers, water heaters, room air-conditioners (RACs), refrigerators, and freezers [134].

Furthermore, the U.S. Department of Energy (DOE) has embraced this methodology for measure lifetime estimation, referencing it in several technical support documents (TSDs) related to various appliances. By adopting these statistical approaches and harnessing comprehensive datasets, it becomes possible to derive a unified and reliable lifetime value for energy conservation measures, addressing the variability inherent in data from different sources.

2.3.2.4 Factors That May Affect the Service Life of ECMs

Often, measures persist longer than their estimated service or technical life, for which reason measure lifetimes are sometimes defined in terms of their effective useful lives (EUL). EUL has two components, the technical life and the measure persistence. While the technical life measures the average length of time that the measure is operational [126] (Hoffman, et al., 2015), the measure persistence measures the actual time that the measure lasts when factors such as home turnover, early retirement of installed equipment, or retrofits and remodeling, are considered [125], [127].

Where installed measures have a limited warranty, it is rightly assumed that such measures will last no less than the warranty period and may persist longer as is often the case with most measures. For this reason, ECM lifetimes that are based on manufacturer warranty may reasonably be allowed a persistence allowance beyond the warranty period during which the measure would still be functional or deemed to be so. For insulation materials which are known to degrade over time, there is no standardized methodology to examine the service life or decay of the material’s thermal performance over its operation phase within EPD framework [162]. However, there are known ways in which some insulation materials may lose their thermal insulation properties and, consequently, reduce their service life. For example, of radiant barriers, [163] discuss four elements that may cause their surface emittance to degrade which includes dust and other contaminants, moisture condensation, corrosion, and oxide films. It is therefore important to consider the environment in which measures are installed, and the maintenance of such measures to estimate their service lives, regardless of warranties or EPD reference service lives or available information in public databases.

2.3.3 Proposal of remaining work

Existing literature that supports life-cycle cost analysis for energy efficiency retrofits provides projections for 30 years. There are calls by energy auditors to have projections that can help them do life-cycle cost analysis that span beyond 30 years, even up to 50 years. This is true for some envelope measures such as certain batt and blown-in insulations which are proven to last 50 years or more. To account for projections beyond 30 years, NIST advises the use of simple extrapolations of the 30th year growth rates as employed in the Building Life-Cycle Cost (BLCC) program [164]. The simple extrapolation method was given to help meet certain federal requirements such as FEMP service period of up to 40 years for government-owned or operated buildings. Also, according NREL’s “Manual for the Economic Evaluation of Energy Efficiency and Renewable Energy Technologies” [165], projects with terms longer than 30 years may use the 30-year discount rate.

These oversimplified methodologies for analyzing measures with lifetimes beyond 30 years will be reexamined in this research in order to provide a more viable methodology for such analyses.

3. List of current and potential publications

3.1 Current publications

- **Amoo, Charles**, Malhotra, Mini, and Eckman, Bill (2023). Evaluation Methodology for Measure Allowable Lifetimes in Weatherization Assistance Program. ORNL Internal Report. (under review)

- Malhotra, Mini, Eckman, Bill, Fishbaugher, Mark and **Amoo, Charles** (2023). The Weatherization Assistant Engineering Manual (Version 8.9). ORNL Internal Report (submitted for review)

- Malhotra, Mini, Eckman, Bill and **Amoo, Charles** (2023). Web-based Weatherization Assistant Getting Started Guide. ORNL Internal Report. https://weatherization.ornl.gov/wp-content/uploads/2022/07/Web-Based-WA-Getting-Started-Guideline-05-08-2020.pdf
- Bass, Brett, New, Joshua R., Clinton, Nicholas, Adams, Mark, Copeland, Bill and **Amoo, Charles** (2022). "How close are urban scale building simulations to measured data? Examining bias derived from building metadata in urban building energy modeling." Journal of Applied Energy, volume 327(1), doi.org/10.1016/j.apenergy.2022.120049, Dec. 1, 2022. https://doi.org/10.1016/j.apenergy.2022.120049
- Bass, Brett, New, Joshua, **Amoo, Charles**, Ezell, Evan and Copeland, William (2021). "Using Measured Building Energy Data to Infer Building Type for Building Energy Modeling." ASHRAE/IBPSA-USA 2022 Building Performance Analysis Conference and SimBuild (BPACS), Chicago, IL, Sept. 14-16, 2022. PDF PPT

3.2 Potential publications related to dissertation

- **Amoo, Charles N.**, New, Joshua R. and Eckman, Bill. (2023). A multicriteria framework for assessing energy audit software for low-income households in the United States. Journal of Energy and Buildings (undergoing internal reviews before submission to journal)
- **Amoo, C. N.** et al. (2024). Evaluating the Lifetimes of Energy Conservation Measures in Low-Income Housing: A Systematic and Repeatable Methodology
- **Amoo, C**. N. et al. (2024). A Novel Approach to Evaluating ECM Lifetimes beyond 30 years for Low-Income Residential Housing.
- **Amoo, C. N.** et al. (2024). A Practical Demonstration of a Multicriteria Framework for Energy Audit Software in Low-Income Homes.

4. Timeline of research progress/milestones

Student Name	**CHARLES NII-BAAH AMOO**
Principal Supervisor	**Dr. Joshua New**
Committee Advisors	**Dr. Hongyu Zhou, Dr Joshua Fu, Dr. Chien-Fei Chen**
Research Topic	**Low-Income Energy Efficiency Programs: A Multicriteria Framework for Energy Audit Software and Evaluation Methodologies for ECMs**
Current as at	**Oct-22**

	2021				2022				2023				2024			
	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall	Winter	Spring	Summer	Fall
Literature review																
Coursework																
Qualifying exams																
Seminars/Conference																
Understanding energy audit needs																
Dev't of energy audit assessment framewo																
Preparation/submission of journal paper																
Review of existing audit tools																
Comprehensive Exams																
Preparation/submission of journal paper																
Conference submission/presentation																
Measure lifetitime economic analysis																
Preparation/submission of journal paper																
Begin dissertation writing																
Review dissertation writing																
Incorporate feedback																
Final thesis defense																
Graduate																

5. Acknowledgement

The author wants to thank PhD advisor Dr. Joshua New as well as PhD committee advisors Dr. Hongyu Nick Zhou, Dr. Joshua S. Fu and Dr. Chien-Fei Chen for their direction on various aspects of this dissertation proposal.

6. List of references and bibliography

[1] B. Bass, J. New, N. Clinton, M. Adams, B. Copeland, and C. Amoo, “How close are urban scale building simulations to measured data? Examining bias derived from building metadata in urban building energy modeling,” *Applied Energy*, vol. 327, p. 120049, Dec. 2022, doi: 10.1016/j.apenergy.2022.120049.

[2] International Energy Agency, “Buildings: A source of enormous untapped efficiency potential,” IEA. Accessed: Mar. 24, 2022. [Online]. Available: https://www.iea.org/topics/buildings

[3] I. Hamilton, H. Kennard, S. Zuhaib, O. Rapf, and J. Kockat, “2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector,” United Nations Environment Program, Dec. 2020. Accessed: Feb. 01, 2023. [Online]. Available: https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf

[4] U.S. Energy Information Administration, “Revenue from Sales of Electricity to Ultimate Customers.” Accessed: Feb. 01, 2023. [Online]. Available: https://www.eia.gov/electricity/annual/html/epa_02_03.html

[5] C. Delmastro, “Buildings: Sectorial Overview,” International Energy Agency (IEA), Paris, License: CC BY 4.0, Sep. 2022. Accessed: Apr. 04, 2023. [Online]. Available: https://www.iea.org/reports/buildings

[6] U.S. Energy Information Administration, “International Energy Outlook 2021,” Oct. 2021. Accessed: Apr. 04, 2023. [Online]. Available: https://www.eia.gov/outlooks/ieo/consumption/sub-topic-03.php

[7] M. Santamouris and K. Vasilakopoulou, “Present and future energy consumption of buildings: Challenges and opportunities towards decarbonisation,” *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 1, p. 100002, Jan. 2021, doi: 10.1016/j.prime.2021.100002.

[8] U.S. Office of State and Community Energy Programs, “Low-Income Community Energy Solutions,” Energy.gov. Accessed: Apr. 13, 2023. [Online]. Available: https://www.energy.gov/scep/slsc/low-income-community-energy-solutions

[9] U.S. Census Bureau, “U.S. Department of Energy Uses ACS Data to Power the Low-income Energy Affordability Data (LEAD) Tool,” Census.gov. Accessed: Apr. 04, 2023. [Online]. Available: https://www.census.gov/programs-surveys/acs/about/acs-data-stories/lead-tool.html

[10] International Energy Agency, “Global energy efficiency progress is accelerating, signalling a potential turning point after years of slow improvement - News,” IEA. Accessed: Feb. 02, 2023. [Online]. Available: https://www.iea.org/news/global-energy-efficiency-progress-is-accelerating-signalling-a-potential-turning-point-after-years-of-slow-improvement

[11] U.S. Office of State and Community Energy Programs, “Energy Efficiency Potential Studies Catalog,” Energy.gov. Accessed: Feb. 02, 2023. [Online]. Available: https://www.energy.gov/scep/slsc/energy-efficiency-potential-studies-catalog

[12] U.S. Office of State and Community Energy Programs, “Office of State and Community Energy Programs,” Energy.gov. Accessed: Apr. 04, 2023. [Online]. Available: https://www.energy.gov/scep/office-state-and-community-energy-programs

[13] U.S. Office of Energy Efficiency and Renewable Energy, “Building Technology Office Multi-Year Program Plan,” Feb. 2016. [Online]. Available: https://www.energy.gov/sites/default/files/2016/02/f29/BTO%20Multi-Year%20Program%20Plan%20-%20Final.pdf

[14] International Energy Agency, “Energy efficiency and digitalisation – Analysis,” IEA. Accessed: Feb. 02, 2023. [Online]. Available: https://www.iea.org/articles/energy-efficiency-and-digitalisation

[15] U.S. Department of Energy, “Better Buildings Initiative | U.S. Department of Energy.” Accessed: Feb. 02, 2023. [Online]. Available: https://betterbuildingssolutioncenter.energy.gov/

[16] U.S. Department of Energy, “Better Climate Challenge | Better Buildings Initiative.” Accessed: Feb. 02, 2023. [Online]. Available: https://betterbuildingssolutioncenter.energy.gov/climate-challenge

[17] U.S. Office of Energy Efficiency and Renewable Energy, “About Energy Saver,” Energy.gov. Accessed: Feb. 02, 2023. [Online]. Available: https://www.energy.gov/energysaver/about-energy-saver

[18] U.S. Office of State and Community Energy Programs, “About the Weatherization Assistance Program,” Energy.gov. Accessed: Feb. 02, 2023. [Online]. Available: https://www.energy.gov/scep/wap/about-weatherization-assistance-program

[19] U.S. Office of Energy Efficiency and Renewable Energy, “Review of Selected Home Energy Auditing Tools,” U. S. Office of Energy Efficiency and Renewable Energy, Nov. 2010. Accessed: Jan. 04, 2023. [Online]. Available: https://www.energy.gov/eere/buildings/articles/review-selected-home-energy-auditing-tools

[20] J. Leung, “Decarbonizing U.S. Buildings,” Center for Climate and Energy Solutions, Jul. 2018. Accessed: Feb. 01, 2023. [Online]. Available: https://www.c2es.org/document/decarbonizing-u-s-buildings/

[21] I. IEA, "Perspectives for the Clean Energy Transition. The Critical Role of Buildings," International Energy Agency (IEA), 2019. Accessed: Sep. 11, 2023. [Online]. Available: https://iea.blob.core.windows.net/assets/026bff1b-821d-48bc-8a0e-7c10280c62bc/Perspectives_for_the_Clean_Energy_Transition_2019.pdf

[22] D. M. Grueneich, "The Next Level of Energy Efficiency: The Five Challenges Ahead," *The Electricity Journal*, vol. 28, no. 7, pp. 44–56, Aug. 2015, doi: 10.1016/j.tej.2015.07.001.

[23] NRDC, "Plug-In Equipment Efficiency: A Key Strategy to Help Achieve California's Carbon Reduction and Clean Energy Goals," p. 5, 2015. Accessed: Sep. 12, 2023. [Online]. Available: https://www.nrdc.org/sites/default/files/home-idle-load-plug-in-efficiency-IB.pdf

[24] D. Grueneich and D. Jacot, "Scale, Speed, and Persistence in an Analytics Age of Efficiency: How Deep Data Meets Big Savings to Deliver Comprehensive Efficiency," *The Electricity Journal*, vol. 27, no. 3, pp. 77–86, Apr. 2014, doi: 10.1016/j.tej.2014.03.001.

[25] V. Ekstrom, "Opportunities, Challenges for Energy Efficiency," MIT Energy Initiative. Accessed: Sep. 14, 2023. [Online]. Available: https://energy.mit.edu/news/opportunities-challenges-for-energy-efficiency/

[26] National Renewable Energy Laboratory, "Summary of Gaps and Barriers for Implementing Residential Building Energy Efficiency Strategies," U. S. Office of Energy Efficiency and Renewable Energy, Aug. 2010. Accessed: Sep. 08, 2023. [Online]. Available: https://www.energy.gov/eere/buildings/articles/summary-gaps-and-barriers-implementing-residential-building-energy

[27] B. Potter, "Every Building in America - an Analysis of the US Building Stock," Construction Physics. Accessed: Jul. 12, 2023. [Online]. Available: https://www.construction-physics.com/p/every-building-in-america-an-analysis

[28] "Procedures for Commercial Building Energy Audits." Accessed: Jul. 12, 2023. [Online]. Available: https://www.ashrae.org/technical-resources/bookstore/procedures-for-commercial-building-energy-audits

[29] *WPN 22-10: Including Non-Energy Impacts within the Weatherization Assistance Program*, (Nov. 17, 2022). Accessed: Jul. 12, 2023. [Online Video]. Available: https://www.youtube.com/watch?v=tGWHwRWGCtc

[30] U.S. Office of State and Community Energy Programs, "Energy Efficiency Policies and Programs," Energy.gov. Accessed: Oct. 09, 2023. [Online]. Available: https://www.energy.gov/scep/slsc/energy-efficiency-policies-and-programs

[31] U.S. Office of Energy Efficiency and Renewable Energy, "The Energy Audit Process & State Applications," presented at the Energy Assessment TAP Webinar Series, May 23, 2013. [Online]. Available: https://www.energy.gov/sites/prod/files/2014/05/f15/theenergyauditprocessandstateapplications.pdf

[32] U.S. Department of Energy, "Building Technologies Program: A Guide to Energy Audit," Pacific Northwest National Laboratory, PNNL-20956, Sep. 2011. Accessed: Feb. 07, 2023. [Online]. Available: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-20956.pdf

[33] I. Shapiro, "10 Common Problems in Energy Audits," *ASHRAE Journal*, 2011, Accessed: Feb. 21, 2023. [Online]. Available: https://www.taitem.com/wp-content/uploads/2011/02/026-033_shapiro.pdf

[34] Bureau of Energy Efficiency, "Energy Management and Audit," in *General Aspect of Energy Management and Energy Audit*, 2005, p. 25. Accessed: Jul. 05, 2023. [Online]. Available: https://beeindia.gov.in/sites/default/files/1Ch3.pdf

[35] "Energy Audit Software," Bizee Energy Audit Software. Accessed: Jul. 12, 2023. [Online]. Available: https://www.energyauditsoftware.com/

[36] R. Leicht, S. Oggianu, Y. M. Lee, and B. Mace, "Energy Audit Tool Overview," Consortium for Building Energy Innovation (CBEI), Pennsylvania, Jan. 2013. Accessed: Jul. 12, 2023. [Online]. Available: http://cbei.psu.edu/wp-content/uploads/2016/07/Energy-Audit-Tool-Overview.pdf

[37] A. S. Berres, B. C. Bass, M. B. Adams, E. Garrison, and J. R. New, "A Data-Driven Approach to Nation-Scale Building Energy Modeling," in *2021 IEEE International Conference on Big Data (Big Data)*, Orlando, FL, USA: IEEE, Dec. 2021, pp. 1558–1565. doi: 10.1109/BigData52589.2021.9671786.

[38] Office of Energy Efficiency and Renewable Energy, "Introduction to eGuide Level 2." Accessed: Jul. 21, 2023. [Online]. Available: https://www1.eere.energy.gov/manufacturing/eguide/iso_step_2_6.html

[39] A. Oraiopoulos and B. Howard, "On the accuracy of Urban Building Energy Modelling," *Renewable and Sustainable Energy Reviews*, vol. 158, p. 111976, Apr. 2022, doi: 10.1016/j.rser.2021.111976.

[40] "ANSI/ASHRAE Addendum a to ANSI/ASHRAE Standard 140-2017: Standard Method of Test for the Evaluation of Building Energy Analysis Computer Programs".

[41] "ASHRAE Standard 140 Maintenance and Development," Energy.gov. Accessed: Feb. 23, 2023. [Online]. Available: https://www.energy.gov/eere/buildings/ashrae-standard-140-maintenance-and-development

[42] J. Neymark, "BESTEST-EX Meeting," Feb. 17, 2023.

[43] National Renewable Energy Laboratory, “BESTEST-EX: Building Energy Simulation Test for Existing Homes.” Accessed: Feb. 23, 2023. [Online]. Available: https://www.nrel.gov/buildings/bestest-ex.html
[44] R. Judkoff, B. Polly, M. Bianchi, J. Neymark, and M. Kennedy, “Building Energy Simulation Test for Existing Homes (BESTEST-EX): Instructions for Implementing the Test Procedure, Calibration Test Reference Results, and Example Acceptance-Range Criteria,” NREL/TP-5500-52414, 1025059, Aug. 2011. doi: 10.2172/1025059.
[45] R. Judkoff, B. Polly, M. Bianchi, and J. Neymark, “Example Procedures for Developing Acceptance-Range Criteria for BESTEST-EX,” Aug. 2010, doi: 10.2172/1218839.
[46] R. Judkoff, J. Neymark, B. Polly, and M. Bianchi, “Building Energy Simulation Test for Existing Homes (BESTEST-EX) Phase 1 Test Procedure: Building Thermal Fabric Cases,” National Renewable Energy Laboratory, NREL/TP-550-47427, Aug. 2010. doi: 10.2172/1219607.
[47] R. Judkoff, B. Polly, M. Bianchi, and J. Neymark, “Building Energy Simulation Test for Existing Homes (BESTEST-EX) Methodology: Preprint,” p. 10, Nov. 2011, doi: 10.2172/1029029.
[48] B. Polly, N. Kruis, and D. Roberts, “Assessing and Improving the Accuracy of Energy Analysis for Residential Buildings,” National Renewable Energy Lab. (NREL), Golden, CO (United States), DOE/GO-102011-3243, Jul. 2011. doi: 10.2172/1219220.
[49] D. Coakley, P. Raftery, and M. Keane, “A review of methods to match building energy simulation models to measured data,” *Renewable and Sustainable Energy Reviews*, vol. 37, pp. 123–141, Sep. 2014, doi: 10.1016/j.rser.2014.05.007.
[50] Y. Chen, M. Guo, Z. Chen, Z. Chen, and Y. Ji, “Physical energy and data-driven models in building energy prediction: A review,” *Energy Reports*, vol. 8, pp. 2656–2671, 2022, doi: https://doi.org/10.1016/j.egyr.2022.01.162.
[51] “About Building Energy Modeling,” Energy.gov. Accessed: Mar. 07, 2023. [Online]. Available: https://www.energy.gov/eere/buildings/about-building-energy-modeling
[52] D. Kim, J. Lee, S. Do, P. J. Mago, K. H. Lee, and H. Cho, “Energy Modeling and Model Predictive Control for HVAC in Buildings: A Review of Current Research Trends,” *Energies*, vol. 15, no. 19, 2022, doi: 10.3390/en15197231.
[53] H. Sha, P. Xu, Z. Yang, Y. Chen, and J. Tang, “Overview of computational intelligence for building energy system design,” *Renewable and Sustainable Energy Reviews*, vol. 108, pp. 76–90, Jul. 2019, doi: 10.1016/j.rser.2019.03.018.
[54] U.S. Department of Energy, “EnergyPlus.” Sep. 30, 2022. Accessed: Mar. 07, 2023. [Online]. Available: https://energyplus.net/
[55] U.S. Department of Energy, “eQuest and DOE-2.” 2016. Accessed: Mar. 07, 2023. [Online]. Available: https://www.doe2.com/
[56] IBPSA-USA, “Search Software and Training | Best Directory.” Accessed: Mar. 07, 2023. [Online]. Available: https://www.buildingenergysoftwaretools.com/software-listing?keywords=&field_catagory_tid%5B%5D=201&field_catagory_tid%5B%5D=203&field_building_type_tid%5B%5D=618&field_building_type_tid%5B%5D=651&field_platform_tid=All&field_price_tid=All&field_last_updated_value%5Bvalue%5D%5Byear%5D=2010&field_language_tid=All&keys=&sort_by=field_rating_rating&sort_order=DESC&items_per_page=40
[57] D. Mazzeo, N. Matera, C. Cornaro, G. Oliveti, P. Romagnoni, and L. D. Santoli, “EnergyPlus, IDA ICE and TRNSYS predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a PCM module,” *Energy and Buildings*, vol. 212, p. 109812, 2020, doi: https://doi.org/10.1016/j.enbuild.2020.109812.
[58] M. H. Shamsi, U. Ali, E. Mangina, and J. O’Donnell, “Feature assessment frameworks to evaluate reduced-order grey-box building energy models,” *Applied Energy*, vol. 298, p. 117174, 2021, doi: https://doi.org/10.1016/j.apenergy.2021.117174.
[59] S. Estrada-Flores, I. Merts, B. D. Ketelaere, and J. Lammertyn, “Development and validation of ‘grey-box’ models for refrigeration applications: A review of key concepts,” *International Journal of Refrigeration*, vol. 29, no. 6, pp. 931–946, 2006, doi: https://doi.org/10.1016/j.ijrefrig.2006.03.018.
[60] J. Dong, C. Winstead, J. Nutaro, and T. Kuruganti, “Occupancy-Based HVAC Control with Short-Term Occupancy Prediction Algorithms for Energy-Efficient Buildings,” *Energies*, vol. 11, no. 9, 2018, doi: 10.3390/en11092427.
[61] Y. Li, Z. O’Neill, L. Zhang, J. Chen, P. Im, and J. DeGraw, “Grey-box modeling and application for building energy simulations - A critical review,” *Renewable and Sustainable Energy Reviews*, vol. 146, p. 111174, 2021, doi: https://doi.org/10.1016/j.rser.2021.111174.

[62] J. Ma and J. C. P. Cheng, “Estimation of the building energy use intensity in the urban scale by integrating GIS and big data technology,” *Applied Energy*, vol. 183, pp. 182–192, Dec. 2016, doi: 10.1016/j.apenergy.2016.08.079.
[63] H. Liu, J. Liang, Y. Liu, and H. Wu, “A Review of Data-Driven Building Energy Prediction,” *Buildings*, vol. 13, no. 2, Art. no. 2, Feb. 2023, doi: 10.3390/buildings13020532.
[64] G. Tardioli, R. Kerrigan, M. Oates, J. O‘Donnell, and D. Finn, “Data Driven Approaches for Prediction of Building Energy Consumption at Urban Level,” *Energy Procedia*, vol. 78, pp. 3378–3383, 2015, doi: https://doi.org/10.1016/j.egypro.2015.11.754.
[65] B. J. Williams and J. C. Carver, “Characterizing software architecture changes: A systematic review,” *Information and Software Technology*, vol. 52, no. 1, pp. 31–51, Jan. 2010, doi: 10.1016/j.infsof.2009.07.002.
[66] Order Group, “Importance of Flexibility in Software Project Management.” Accessed: Mar. 02, 2023. [Online]. Available: https://ordergroup.co/blog/why-is-flexibility-such-a-valuable-trait-in-software-development/
[67] D. L. Parnas, “Designing Software for Ease of Extension and Contraction,” *IEEE Transactions on Software Engineering*, vol. SE-5, no. 2, pp. 128–138, Mar. 1979, doi: 10.1109/TSE.1979.234169.
[68] R. D. Austin and L. Devin, “Research Commentary: Weighing the Benefits and Costs of Flexibility in Making Software: Toward a Contingency Theory of the Determinants of Development Process Design,” *Information Systems Research*, vol. 20, no. 3, pp. 462–477, 2009, Accessed: Aug. 09, 2023. [Online]. Available: http://www.jstor.org/stable/23015475
[69] G. Breault, “What Is Flexible Technology? (Flexible Vs. Rigid Technology Solutions),” HICX. Accessed: Aug. 09, 2023. [Online]. Available: https://www.hicx.com/blog/what-is-flexible-technology-vs-rigid-solutions/
[70] U.S. Energy Information Administration, “Use of energy in commercial buildings.” Accessed: Mar. 03, 2023. [Online]. Available: https://www.eia.gov/energyexplained/use-of-energy/commercial-buildings.php
[71] M. González-Torres, L. Pérez-Lombard, J. F. Coronel, I. R. Maestre, and D. Yan, “A review on buildings energy information: Trends, end-uses, fuels and drivers,” *Energy Reports*, vol. 8, pp. 626–637, Nov. 2022, doi: 10.1016/j.egyr.2021.11.280.
[72] Y. Xie and A. I. M. Noor, “Factors Affecting Residential End-Use Energy: Multiple Regression Analysis Based on Buildings, Households, Lifestyles, and Equipment,” *Buildings*, vol. 12, no. 5, Art. no. 5, May 2022, doi: 10.3390/buildings12050538.
[73] J. Schoenfeld, “Building Energy Consumption Breakdown for Owners and Management [2023],” BuildingsIOT. Accessed: Aug. 09, 2023. [Online]. Available: https://www.buildingsiot.com/blog/building-energy-consumption-breakdown-for-owners-and-management-bd
[74] U.S. Energy Information Administration, “Use of energy explained: Energy use in homes.” Accessed: Apr. 06, 2023. [Online]. Available: https://www.eia.gov/energyexplained/use-of-energy/homes.php
[75] U.S. Department of Energy, “Chapter 5: Increasing Efficiency of Building Systems and Technologies,” in *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities*, 2015, p. 39. Accessed: Mar. 03, 2023. [Online]. Available: https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter5.pdf
[76] A. W. Brown, P. H. Feiler, and K. C. Wallnau, “Understanding integration in a software development environment,” in *Proceedings of the Second International Conference on Systems Integration*, Jun. 1992, pp. 22–31. doi: 10.1109/ICSI.1992.217286.
[77] ContractSafe, “What does software integration mean? | ContractSafe.” Accessed: Mar. 03, 2023. [Online]. Available: https://www.contractsafe.com/glossary/software-integration
[78] C. M. Monsanto, “Software Integrations: A Beginner’s Guide.” Accessed: Mar. 03, 2023. [Online]. Available: https://blog.hubspot.com/website/software-integration
[79] D. I. Doukas and T. Bruce, “Energy Audit and Renewable Integration for Historic Buildings: The Case of Craiglockhart Primary School,” *Procedia Environmental Sciences*, vol. 38, pp. 77–85, 2017, doi: https://doi.org/10.1016/j.proenv.2017.03.081.
[80] E. J. Weyuker and A. Avritzer, “A metric to predict software scalability,” in *Proceedings Eighth IEEE Symposium on Software Metrics*, Jun. 2002, pp. 152–158. doi: 10.1109/METRIC.2002.1011334.
[81] A. Alexandra and A. Andrew, “Software Scalability: How to Keep Up with Business Growth,” IntexSoft. Accessed: Mar. 03, 2023. [Online]. Available: https://intexsoft.com/blog/software-scalability-how-to-keep-up-with-business-growth/

[82] CyberlinkASP, "What is Software Scalability and Why is it Important?," CyberlinkASP. Accessed: Mar. 03, 2023. [Online]. Available: https://www.cyberlinkasp.com/insights/what-is-software-scalability-and-why-is-it-important/
[83] Z. Li, L. O'Brien, H. Zhang, and R. Cai, "On a Catalogue of Metrics for Evaluating Commercial Cloud Services," in *2012 ACM/IEEE 13th International Conference on Grid Computing*, Sep. 2012, pp. 164–173. doi: 10.1109/Grid.2012.15.
[84] P. Moura and F. Kon, "Automated scalability testing of software as a service," in *2013 8th International Workshop on Automation of Software Test (AST)*, May 2013, pp. 8–14. doi: 10.1109/IWAST.2013.6595784.
[85] A. Al-Said Ahmad and P. Andras, "Scalability analysis comparisons of cloud-based software services," *Journal of Cloud Computing*, vol. 8, no. 1, p. 10, Jul. 2019, doi: 10.1186/s13677-019-0134-y.
[86] A. K. Magapu and N. Yarlagadda, "Performance, Scalability, and Reliability (PSR) challenges, metrics and tools for web testing: A Case Study," Blekinge Institute of Technology, Karlskrona, Sweden, 2016. Accessed: Aug. 10, 2023. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:945974/FULLTEXT02
[87] A. Mjeda and G. Botterweck, "Scalable Software Testing and Verification for Industrial-Scale Systems: The Challenges," *Electronic Communications of the EASST*, vol. 77, no. 0, Art. no. 0, Oct. 2019, doi: 10.14279/tuj.eceasst.77.1111.
[88] S. Naumann, M. Dick, E. Kern, and T. Johann, "The GREENSOFT Model: A reference model for green and sustainable software and its engineering," *Sustainable Computing: Informatics and Systems*, vol. 1, no. 4, pp. 294–304, Dec. 2011, doi: https://doi.org/10.1016/j.suscom.2011.06.004.
[89] S. Murugesan and G. R. Gangadharan, *Harnessing Green IT : Principles and Practices*. New York, UNITED KINGDOM: IEEE Computer Society Press, 2012. [Online]. Available: http://ebookcentral.proquest.com/lib/utk/detail.action?docID=1021187
[90] S. J. Hayter and A. Kandt, "Renewable Energy Applications for Existing Buildings: Preprint," National Renewable Energy Lab. (NREL), Golden, CO (United States), NREL/CP-7A40-52172, Aug. 2011. Accessed: Aug. 11, 2023. [Online]. Available: https://www.osti.gov/biblio/1022419
[91] National Archives and Records Administration, "10 CFR 440.1 -- Purpose and scope.," Code of Federal Regulations. Accessed: Mar. 02, 2023. [Online]. Available: https://www.ecfr.gov/current/title-10/chapter-II/subchapter-D/part-440/section-440.1
[92] A. Chel and G. Kaushik, "Renewable energy technologies for sustainable development of energy efficient building," *Alexandria Engineering Journal*, vol. 57, no. 2, pp. 655–669, Jun. 2018, doi: 10.1016/j.aej.2017.02.027.
[93] US EPA, "Part Two - Chapter 4: Quantifying the Emissions and Health Benefits of Energy Efficiency and Renewable Energy," in *Quantifying the Multiple Benefits of Energy Efficiency and Renewable Energy: A Guide for State and Local Governments*, 2017, p. 68. Accessed: Aug. 11, 2023. [Online]. Available: https://www.epa.gov/statelocalenergy/part-two-chapter-4-quantifying-emissions-and-health-benefits-energy-efficiency-and
[94] K. R. Errickson Brian C. Prest, William A. Pizer, Richard G. Newell, David Anthoff, Cora Kingdon, Lisa Rennels, Roger Cooke, Adrian E. Raftery, Hana Ševčíková, and Frank, "The social cost of carbon," Brookings. Accessed: Apr. 07, 2023. [Online]. Available: https://www.brookings.edu/bpea-articles/the-social-cost-of-carbon/
[95] U.S. Office of State and Community Energy Programs, "Low-Income Community Energy Solutions," Energy.gov. Accessed: Oct. 29, 2022. [Online]. Available: https://www.energy.gov/eere/slsc/low-income-community-energy-solutions
[96] "Income Limits | HUD USER." Accessed: Oct. 29, 2022. [Online]. Available: https://www.huduser.gov/portal/datasets/il.html#2018
[97] U.S. Department of Energy, "Weatherization Assistance Program," U.S. Department of Energy, Aug. 2015. Accessed: Oct. 29, 2022. [Online]. Available: https://www.energy.gov/sites/default/files/2015/08/f25/WAP_NationalEvaluation_WxWorks_v14_blue_8%205%2015.pdf
[98] P. E. Nogueira, R. Matias, and E. Vicente, "An experimental study on execution time variation in computer experiments," in *Proceedings of the 29th Annual ACM Symposium on Applied Computing*, in SAC '14. New York, NY, USA: Association for Computing Machinery, Mar. 2014, pp. 1529–1534. doi: 10.1145/2554850.2555022.
[99] "Explaining the difference between Execution Times and Response Times," Rapita Systems. Accessed: Mar. 04, 2023. [Online]. Available: https://www.rapitasystems.com/blog/explaining-difference-between-execution-times-and-response-times

[100] G. Martinez, J. A. Hernandez, P. Reviriego, and P. Reinheimer, “Round Trip Time (RTT) Delay in the Internet: Analysis and Trends,” *IEEE Network*, pp. 1–6, 2023, doi: 10.1109/MNET004.2300008.
[101] Imperva, “What is Round Trip Time (RTT) | Behind the Ping | CDN Guide | Imperva,” Learning Center. Accessed: Apr. 11, 2023. [Online]. Available: https://www.imperva.com/learn/performance/round-trip-time-rtt/
[102] T. Duminil, “Doriane | Blog — What makes research software user-friendly?,” Doriane Research Software and Consulting. Accessed: Feb. 28, 2023. [Online]. Available: https://www.doriane.com/blog/user-friendly-research-software
[103] E. Haghbayan Roudbaraki, “Analyzing User-Friendly Software Designs to Improve Customer Satisfaction,” *SSRN Journal*, 2022, doi: 10.2139/ssrn.4064559.
[104] A. Raza, L. F. Capretz, and S. B. Basri, “An Empirical Study of User Support Tools in Open Source Software,” in *2019 IEEE 15th International Conference on Control and Automation (ICCA)*, Jul. 2019, pp. 964–968. doi: 10.1109/ICCA.2019.8899935.
[105] T. D. Lundgren, “End-User Support,” *Journal of Computer Information Systems*, vol. 39, no. 1, pp. 60–64, Sep. 1998, doi: 10.1080/08874417.1998.11647375.
[106] S. Wood and R. J. Howlett, “A Web-Based Customer Support Knowledge Base System,” in *Knowledge-Based Intelligent Information and Engineering Systems*, I. Lovrek, R. J. Howlett, and L. C. Jain, Eds., in Lecture Notes in Computer Science. Berlin, Heidelberg: Springer, 2008, pp. 349–361. doi: 10.1007/978-3-540-85563-7_47.
[107] D. Korenova and A. Cepelova, “Factors influencing process management and effective operation of public administration organizations,” *Актуальні проблеми економіки*, no. 3, pp. 80–88, 2016.
[108] A. Fabijan, H. H. Olsson, and J. Bosch, “Customer Feedback and Data Collection Techniques in Software R&D: A Literature Review,” in *Software Business*, J. M. Fernandes, R. J. Machado, and K. Wnuk, Eds., in Lecture Notes in Business Information Processing. Cham: Springer International Publishing, 2015, pp. 139–153. doi: 10.1007/978-3-319-19593-3_12.
[109] S. Lehmann and P. Buxmann, “Pricing Strategies of Software Vendors,” *Bus. Inf. Syst. Eng.*, vol. 1, no. 6, pp. 452–462, Dec. 2009, doi: 10.1007/s12599-009-0075-y.
[110] “Definition of Business to Business (B2B) Sales - Gartner Sales Glossary,” Gartner. Accessed: Mar. 02, 2023. [Online]. Available: https://www.gartner.com/en/sales/glossary/business-to-business-b2b-sales
[111] D. Ferrante, “Software Licensing Models: What’s Out There?,” *IT Professional*, vol. 8, no. 6, pp. 24–29, Nov. 2006, doi: 10.1109/MITP.2006.147.
[112] J. Rodrigues, P. Ruivo, and T. Oliveira, “Software as a Service Value and Firm Performance - A literature Review Synthesis in Small and Medium Enterprises,” *Procedia Technology*, vol. 16, pp. 206–211, Jan. 2014, doi: 10.1016/j.protcy.2014.10.085.
[113] L. Harvey, “The Ultimate Guide to Smart Software Pricing Strategies | Toptal®,” Toptal Product Blog. Accessed: Mar. 02, 2023. [Online]. Available: https://www.toptal.com/product-managers/product-management/software-pricing-strategy-and-architecture
[114] “Software Pricing Models: Enterprise SaaS Pricing Models & Strategies.” Accessed: Mar. 02, 2023. [Online]. Available: https://cpl.thalesgroup.com/software-monetization/saas-pricing-models
[115] “Accessibility - W3C.” Accessed: Mar. 03, 2023. [Online]. Available: https://www.w3.org/standards/webdesign/accessibility
[116] A. Mishra, “Why Accessibility in Software Development Matters,” Adeva. Accessed: Mar. 03, 2023. [Online]. Available: https://adevait.com/software/accessibility-in-software-development
[117] T. Davis, “Measuring the Success of Your Software Projects,” 3Pillar Global. Accessed: Mar. 02, 2023. [Online]. Available: https://www.3pillarglobal.com/insights/measuring-the-success-of-your-software-development-projects/
[118] S. Caputo, L. Cascio, S. Jean-Baptiste, C. Tanner, and E. Titus, “Non-Energy Impacts Approaches and Values: An Examination of the Northeast, Mid-Atlantic, and Beyond,” Northeast Energy Efficiency Partnership, 97, Jun. 2017. Accessed: Apr. 11, 2023. [Online]. Available: https://neep.org/sites/default/files/resources/NEI%20Final%20Report%20for%20NH%20updated%2010.4.17.pdf
[119] M. Freed and F. A. Felder, “Non-energy benefits: Workhorse or unicorn of energy efficiency programs?,” *The Electricity Journal*, vol. 30, no. 1, pp. 43–46, Jan. 2017, doi: 10.1016/j.tej.2016.12.004.
[120] S. Outcault, A. Sanguinetti, N. Dessouky, and C. Magaña, “Occupant Non-Energy Impact Identification Framework: A human-centered approach to understanding residential energy retrofits,” *Energy and Buildings*, vol. 263, p. 112054, May 2022, doi: 10.1016/j.enbuild.2022.112054.

[121] O. US EPA, "Adapting Buildings for Indoor Air Quality in a Changing Climate." Accessed: Sep. 01, 2023. [Online]. Available: https://www.epa.gov/indoor-air-quality-iaq/adapting-buildings-indoor-air-quality-changing-climate
[122] A. Syazwan *et al.*, "Development of an indoor air quality checklist for risk assessment of indoor air pollutants by semiquantitative score in nonindustrial workplaces," *Risk Manag Healthc Policy*, vol. 5, pp. 17–23, Apr. 2012, doi: 10.2147/RMHP.S26567.
[123] U.S. Office of State and Community Energy Programs, "ARCHIVED Weatherization Program Notice 19-4: Revised Energy Audit Approval Procedures, Related Audit, and Material Approvals," Energy.gov. Accessed: Oct. 11, 2023. [Online]. Available: https://www.energy.gov/scep/wap/articles/archived-weatherization-program-notice-19-4-revised-energy-audit-approval
[124] U.S. Office of State and Community Energy Programs, "Weatherization Energy Audits," Energy.gov. Accessed: Feb. 02, 2023. [Online]. Available: https://www.energy.gov/scep/wap/weatherization-energy-audits
[125] S. R. Schiller, "Energy Efficiency Program Impact Evaluation Guide," State and Local Energy Efficiency Action Network, DOE/EE-0829, 2012. Accessed: Oct. 16, 2023. [Online]. Available: https://www.energy.gov/eere/articles/energy-efficiency-program-impact-evaluation-guide
[126] I. M. Hoffman, S. R. Schiller, A. Todd, M. A. Billingsley, C. A. Goldman, and L. C. Schwartz, "Energy Savings Lifetimes and Persistence," Lawrence Berkeley National Laboratory, Berkeley, California, LBNL--179191, 1236443, Feb. 2016. doi: 10.2172/1236443.
[127] R. Gold and S. Nowak, "Energy Efficiency Over Time: Measuring and Valuing Lifetime Energy Savings in Policy and Planning." Washington, DC: ACEEE. aceee. org/researchreport, 2019. Accessed: Oct. 16, 2023. [Online]. Available: https://www.nationalenergyscreeningproject.org/wp-content/uploads/2019/02/ACEEE_EE_over_time_measuring_valuing_lifetime_savings_2019.pdf
[128] H. D. Tolley, J. M. Barnes, and M. D. Freeman, "Chapter 10 - Survival Analysis," in *Forensic Epidemiology*, M. D. Freeman and M. P. Zeegers, Eds., Amsterdam: Academic Press, 2016, pp. 261–284. doi: 10.1016/B978-0-12-404584-2.00010-0.
[129] D. P. Loucks and E. van Beek, "An Introduction to Probability, Statistics, and Uncertainty," in *Water Resource Systems Planning and Management: An Introduction to Methods, Models, and Applications*, D. P. Loucks and E. van Beek, Eds., Cham: Springer International Publishing, 2017, pp. 213–300. doi: 10.1007/978-3-319-44234-1_6.
[130] X.-S. Si, W. Wang, C.-H. Hu, and D.-H. Zhou, "Remaining useful life estimation – A review on the statistical data driven approaches," *European Journal of Operational Research*, vol. 213, no. 1, pp. 1–14, Aug. 2011, doi: 10.1016/j.ejor.2010.11.018.
[131] M. J. Bradburn, T. G. Clark, S. B. Love, and D. G. Altman, "Survival Analysis Part II: Multivariate data analysis – an introduction to concepts and methods," *Br J Cancer*, vol. 89, no. 3, Art. no. 3, Aug. 2003, doi: 10.1038/sj.bjc.6601119.
[132] P. Schober and T. R. Vetter, "Survival Analysis and Interpretation of Time-to-Event Data: The Tortoise and the Hare," *Anesthesia & Analgesia*, vol. 127, no. 3, p. 792, Sep. 2018, doi: 10.1213/ANE.0000000000003653.
[133] T. K. Kim, "T test as a parametric statistic," *Korean J Anesthesiol*, vol. 68, no. 6, pp. 540–546, Nov. 2015, doi: 10.4097/kjae.2015.68.6.540.
[134] J. D. Lutz, A. Hopkins, V. Letschert, V. H. Franco, and A. Sturges, "Using national survey data to estimate lifetimes of residential appliances," *HVAC&R Research*, vol. 17, no. 5, pp. 726–736, Oct. 2011, doi: 10.1080/10789669.2011.558166.
[135] S. Kara, S. Manmek, H. Kaebernick, and S. Ibbotson, "Assessment of products for optimal lifetime," *CIRP Annals*, vol. 57, no. 1, pp. 1–4, Jan. 2008, doi: 10.1016/j.cirp.2008.03.116.
[136] "Energy Conservation Program: Energy Conservation Standards for Residential Water Heaters, Direct Heating Equipment, and Pool Heaters," Federal Register. Accessed: Oct. 23, 2023. [Online]. Available: https://www.federalregister.gov/documents/2010/04/16/2010-7611/energy-conservation-program-energy-conservation-standards-for-residential-water-heaters-direct
[137] S. Whiteford, "Real Property Asset Management — DOE Directives, Guidance, and Delegations." Accessed: Oct. 21, 2023. [Online]. Available: https://www.directives.doe.gov/directives-documents/400-series/0430.1-BOrder-c-chg2-adminchg
[138] "ANSI Introduction," American National Standards Institute - ANSI. Accessed: Oct. 21, 2023. [Online]. Available: https://www.ansi.org/about/introduction
[139] "About ASHRAE | ashrae.org." Accessed: Oct. 21, 2023. [Online]. Available: https://www.ashrae.org/about
[140] "About NIST," *NIST*, Jul. 2009, Accessed: Oct. 21, 2023. [Online]. Available: https://www.nist.gov/about-nist

[141] "ISO - Benefits of standards," ISO. Accessed: Oct. 21, 2023. [Online]. Available: https://www.iso.org/benefits-of-standards.html
[142] ASHRAE, *2019 ASHRAE Handbook: HVAC Applications*, 2019th ed. Atlanta, Georgia: American Society of Heating, Refrigerating and Air-Conditioning Engineers,Atlanta,Georgia,United States of America, 2020. Accessed: Oct. 21, 2023. [Online]. Available: https://www.osti.gov/biblio/1651418
[143] The World Bank, "Field Surveys - Dimewiki." Accessed: Oct. 23, 2023. [Online]. Available: https://dimewiki.worldbank.org/Field_Surveys
[144] M. A. Martin and M. B. Gettings, "Review of water, lighting, and cooling energy efficiency measures for low-income homes located in warm climates," Oak Ridge National Lab. (ORNL), Oak Ridge, TN (United States), ORNL/CON-437, Feb. 1998. doi: 10.2172/607493.
[145] M. P. Ternes, P. S. Hu, L. S. Williams, and P. Goewey, "The national fuel end-use efficiency field test: Energy savings and performance of an improved energy conservation measure selection technique," Oak Ridge National Lab., TN (USA), ORNL/CON-303, Mar. 1991. Accessed: Oct. 23, 2023. [Online]. Available: https://www.osti.gov/biblio/5678589
[146] C. Xiong, K. Zhu, and K. Yu, "Statistical survival analysis with applications," in *Springer Handbooks*, Springer, 2006, pp. 347–367. Accessed: Oct. 23, 2023. [Online]. Available: https://profiles.wustl.edu/en/publications/statistical-survival-analysis-with-applications
[147] W. Nelson, *Applied Life Data Analysis*, 1st ed. in Wiley Series in Probability and Statistics. Wiley, 1982. doi: 10.1002/0471725234.
[148] B. cheng Wen, M. qing Xiao, X. qi Wang, X. Zhao, J. feng Li, and X. Chen, "Data-driven remaining useful life prediction based on domain adaptation," *PeerJ Computer Science*, vol. 7, p. e690, 2021, Accessed: Oct. 23, 2023. [Online]. Available: https://peerj.com/articles/cs-690/
[149] T. H. Loutas, D. Roulias, and G. Georgoulas, "Remaining useful life estimation in rolling bearings utilizing data-driven probabilistic E-support vectors regression," *IEEE Transactions on Reliability*, vol. 62, no. 4, pp. 821–832, 2013, Accessed: Oct. 23, 2023. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/6645455/
[150] S. S. Ng, Y. Xing, and K. L. Tsui, "A naive Bayes model for robust remaining useful life prediction of lithium-ion battery," *Applied Energy*, vol. 118, pp. 114–123, 2014, Accessed: Oct. 23, 2023. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261913010192
[151] D. Wu, C. Jennings, J. Terpenny, R. X. Gao, and S. Kumara, "A comparative study on machine learning algorithms for smart manufacturing: tool wear prediction using random forests," *Journal of Manufacturing Science and Engineering*, vol. 139, no. 7, p. 071018, 2017, Accessed: Oct. 23, 2023. [Online]. Available: https://asmedigitalcollection.asme.org/manufacturingscience/article-abstract/139/7/071018/454654
[152] M. A. Meyer and J. M. Booker, *Eliciting and Analyzing Expert Judgment: A Practical Guide*. Society for Industrial and Applied Mathematics, 2001. doi: 10.1137/1.9780898718485.
[153] T. P. Obrecht, R. Kunič, S. Jordan, and A. Legat, "Roles of the reference service life (RSL) of buildings and the RSL of building components in the environmental impacts of buildings," *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 323, no. 1, p. 012146, Aug. 2019, doi: 10.1088/1755-1315/323/1/012146.
[154] "The PCR | EPD International." Accessed: Oct. 25, 2023. [Online]. Available: https://www.environdec.com/product-category-rules-pcr/the-pcr
[155] International Organization for Standardization, "ISO 21930:2017," ISO. Accessed: Oct. 25, 2023. [Online]. Available: https://www.iso.org/standard/61694.html
[156] U.S. Green Building Council, "EN 15804—2012 Sustainability of construction works, Environmental product declarations, Core rules for the product category of construction products | U.S. Green Building Council." Accessed: Oct. 25, 2023. [Online]. Available: https://www.usgbc.org/resources/en-15804%E2%80%942012-sustainability-construction-works-environmental-product-declarations-core-ru
[157] A. Grant and R. Ries, "Impact of building service life models on life cycle assessment," *Building Research & Information*, vol. 41, no. 2, pp. 168–186, Apr. 2013, doi: 10.1080/09613218.2012.730735.
[158] A. Grant, R. Ries, and C. Kibert, "Life Cycle Assessment and Service Life Prediction," *Journal of Industrial Ecology*, vol. 18, no. 2, pp. 187–200, 2014, doi: 10.1111/jiec.12089.
[159] M. K. Dixit, "Life cycle recurrent embodied energy calculation of buildings: A review," *Journal of Cleaner Production*, vol. 209, pp. 731–754, Feb. 2019, doi: 10.1016/j.jclepro.2018.10.230.
[160] ASHRAE, "ASHRAE: HVAC Service Life Database." Accessed: Oct. 25, 2023. [Online]. Available: http://weblegacy.ashrae.org/publicdatabase/service_life.asp

[161] J. D. Kneifel and P. D. Lavappa, "Energy price indices and discount factors for life-cycle cost analysis 2022 :: annual supplement to NIST Handbook 135," National Institute of Standards and Technology (U.S.), Gaithersburg, MD, NIST IR 85-3273-37-upd1, May 2022. doi: 10.6028/NIST.IR.85-3273-37-upd1.
[162] J. Kono, Y. Goto, Y. Ostermeyer, R. Frischknecht, and H. Wallbaum, "Factors for Eco-Efficiency Improvement of Thermal Insulation Materials," *Key Engineering Materials*, vol. 678, pp. 1–13, 2016, doi: 10.4028/www.scientific.net/KEM.678.1.
[163] S. W. Lee, C. H. Lim, and E. @ I. B. Salleh, "Reflective thermal insulation systems in building: A review on radiant barrier and reflective insulation," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 643–661, Nov. 2016, doi: 10.1016/j.rser.2016.07.002.
[164] P. D. Lavappa and J. D. Kneifel, "Energy price indices and discount factors for life-cycle cost analysis - 2018 annual supplement to NIST Handbook 135," National Institute of Standards and Technology, Gaithersburg, MD, NIST IR 85-3273-33, Apr. 2018. doi: 10.6028/NIST.IR.85-3273-33.
[165] W. Short, D. J. Packey, and T. Holt, "A manual for the economic evaluation of energy efficiency and renewable energy technologies," National Renewable Energy Lab.(NREL), Golden, CO (United States), NREL/TP-462-5173, 1995. Accessed: Oct. 25, 2023. [Online]. Available: https://www.osti.gov/biblio/35391