Building a Healthy Home: A Comparative Life-Cycle Analysis of Energy-Efficient and Low-VOC Retrofits

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Building a Healthy Home: A Comparative Life-Cycle Analysis of Energy-Efficient and Low-VOC Retrofits

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Abstract

As the main cause of death in America and the leading factor of increased health care costs, chronic illness is a growing concern. While several determinants influence the onset of disease, the surrounding environment, especially residential buildings, plays a significant role in overall health. The sustainable building industry emerged in response to growing concern around climate change, initially as a means to reduce energy use and the burning of fossil fuels. Over the years, it has evolved to include an emphasis on health and wellness, with the potential to mitigate the rising rates of chronic illness.

This thesis compared certification requirements of three green building programs (WELL, LEED, Passive House) to identify differences that may impact health and should be prioritized in the retrofit of a conventional home to a greener home, all else equal. I hypothesized that (1) a retrofit of a conventional home that incorporated green building elements would result in a greater improvement (decrease) in Disability Adjusted Life Years (DALYs) compared to the conventional build and that (2) incorporation of low-VOC materials would result in the greatest improvement (decrease) in DALYS relative to the conventional build and the incorporation of an energy-efficient heat pump.

I utilized SimaPro, the industry-leading life cycle analysis (LCA) software, to evaluate health impacts in terms of DALYs associated with the transition from a conventional model to (1) a Low-VOC Model and (2) an Energy-Efficient Model with a heat pump. Sensitivity analyses included (1) a Low-VOC Model with bamboo flooring, (2) a Low-VOC Model with hardwood flooring, and (3) a Combo Model with both low-

VOC materials and a heat pump. Modeled as 1970’s home in New Jersey, USA, the Conventional Model was modified to incorporate green building elements associated with LEED v4.1 Certified, WELL v2 Certified, and Passive House Institute (i) 10.B guidelines. I collected an inventory of materials, sources and quantities, based on certification criteria within the green building programs, outputs from Athena Impact Estimator, and input from a NJ contractor active in the housing stock.

Findings include that the Low-VOC Model and the Energy-Efficient Model reduced DALYs, with the greatest reduction from the Energy-Efficient Model. A sensitivity analysis indicated that the Low-VOC Model with bamboo flooring and the Low-VOC Model with hardwood flooring slightly reduced DALYs. The Combo Model reduced the most DALYs. Findings were scaled to represent 7%, 10%, 15%, 20%, 25%, 30%, 35%, and 40% of the NJ housing stock to illustrate the impact sustainable building elements could have across a state-wide scale.

In addition to the growing arsenal of optimal building support tools, this thesis proposes practical retrofits for homeowners through LCA methodology. This research is timely, as the 2022 Inflation Reduction Act tax credits and rebates, intended to reduce carbon emissions through national building stock updates and have the potential to improve building health, will begin in 2024. Nevertheless, limitations to LCA methodology (e.g., sparse data on post-production emissions, lifetime material toxicity and associated occupant health impacts) prevent a full understanding of building health. Future improvements to LCA methodology and chemical material standardization would facilitate an ample, objective means to evaluate building health impacts of construction/retrofit activities.

Dedication

To my family, friends, and mentors who have stood by me from the beginning and supported me every step of the way and to everyone who believes in a better world. Thank you.

Acknowledgments

I value greatly certain people in my life, who with their love and support allowed me to write this thesis. Firstly, I thank my thesis director, Dr. Jennifer Senick, for her selfless direction and guidance these past months. Her full devotion to my endeavor, willingness to include me in her team, and continual encouragement of my future goals will always be appreciated. Her dedication to the field of health and sustainable building is an inspiration to my own journey and ambitions in this field. In a similar way, I thank Dr. Mark Leighton, who helped hone and craft my thesis every step of the way, from an idea to proposal and final draft. I would also like to thank other members of the Rutgers University community, particularly Kiran Ghosh and Dr. Uta Krogmann, who took the time to offer helpful insights.

I thank my family, particularly my mother and father, who have allowed me the opportunities of higher education and supported my dreams and goals from a young age. I thank my entire extended family and friends for instilling in me the spark of learning and desire to do better in this world. I especially thank those who encouraged me to find my calling and supported the journey amid difficulties. I am forever grateful.

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Chapter I

Introduction

It is well documented that chronic health conditions have been on the rise throughout the last century. Currently, 60% of Americans suffer from a chronic disease, with 40% having two or more medical conditions (Centers for Disease Control, 2022). These numbers are projected to increase over the next 30 years (Centers for Disease Control, 2022). Chronic conditions such as diabetes, heart disease, and cancer are the primary causes of death in America, as well as the leading factors of increased health care costs (Centers for Disease Control, 2022). While several determinants influence the onset of disease, it is widely known that one's surrounding environment, especially homes and buildings, play a role in overall health (Dreyer et al., 2018).

Americans spend approximately 90% of their time indoors, with 62% of this spent in their place of residence, meaning that exposures to indoor pollutants are potentially significant (Environmental Protection Agency, 2022; Yau, 2023). U.S. residential buildings historically were constructed with materials that pose a negative risk to health (e.g., asbestos, lead, formaldehyde) and disproportionately affect those who live in older housing stock, including lower income communities (U.S. Department of Health and Human Services, 2023). Other types of pollutants commonly found in residential structures include mold and mildew and particulate matter (e.g., PM10, 2.5, ultrafine), all of which pose hazards to building occupant health (U.S. Department of Health and Human Services, 2023).

In 2020, 37% of global GHG emissions were a result of building industry, 69% of which were already constructed buildings (Özdemir, 2022). The sustainable building industry emerged in response to growing concern around climate change, initially as a means to reduce energy use and the burning of fossil fuels, and has grown substantially over the last decade (PNNL, 2022). Through the advancement of technology, infrastructure, and an increase in financial resources, the sustainable building industry is at a pivotal point of feasibility and effectiveness. The green building market is projected to reach a value of over $774 billion by 2030 (Wolf, 2023). Over the years, it has evolved to include an emphasis on health and wellness, with the potential to mitigate the rising rates of chronic illness (PNNL, 2022).

Nevertheless, studies that link well-being to green buildings tend not to be generalized across the industry, as sustainable architecture is a broad industry that includes many different building programs, certification levels, and constituent criteria (e.g., retrofitted Zero Energy Homes (USDOE), Passive House, WELL, LEED). Clearly, not all sustainable buildings are built alike. When associating green buildings with better health outcomes, such as improved productivity, decreased chance of water-borne illness, or improved respiratory health, one must systemically consider a sample of various building programs in a modeled or otherwise controlled analysis. Otherwise, it is difficult to gain valid insight into whether different sustainable-labeled buildings might be expected to have similar health outcomes (Houghton & Castillo-Salgado, 2017; Singh, et al., 2010; Younger et al., 2008).

With chronic illness on the rise, the sustainable building industry must place the same importance on health impacts as it does on reduced energy and water consumption. Research on health impacts of sustainable buildings is still relatively new. There are several possible combinations of green building features that can be employed within a single green building program (LEED Credit Library, 2023). As a result, it is difficult to accurately identify how any single green feature might impact well-being within that program, much less across multiple programs. A current lack of standardized metrics to measure human health impact in buildings is an additional challenge; while there are standardized energy and water performance measures that are codified in green building standards and regulatory/voluntary building guidelines (e.g., building code, building benchmarking disclosure ordinances), similar parameters for factors that influence human well-being do not exist due to the lack of knowledge and the complexity of dose-response (e.g., IAQ measurements) (Congressional Research Service, 2023). Therefore, a better understanding of the relationship between green buildings and health may slow the rapid growth of disease, cut health care costs, and improve mental well-being, productivity, and environmental awareness, among others.

Such research comes at a pivotal time in the United States. Currently, federal and state governments emphasize plans for building decarbonization. The 2022 Inflation Reduction Act tax credits and rebates, which are intended to reduce carbon emissions by 40% by 2030 through advancements to the national building stock, will be available starting in 2024 (*Inflation Reduction Act*, 2022). Plans include $4.5 billion in rebates for low- and moderate- income households to upgrade to new, energy efficient electric appliances, such as rebates to cover the cost of a heat pump, with a cap of $8,000

(*Inflation Reduction Act*, 2022). The Act also offers rebates between $2,000- $4,000 for retrofits that save between 20-35% or more of energy (doubling for low- and moderate-income homes). Additionally, the Memorandum of Understanding, headed by the Northeast States for Coordinated Air Use Management (NESCAUM), recently set a goal for 65% of residential heating, cooling, and water system sales by 2030, and 90% by 2040, to be comprised of heat pumps, with the similar desire to accelerate the transition to pollution-free residences (MacMunn, 2024). Participating states will "collect market data, track progress, and develop an action plan" for residential electrification (MacMunn, 2024).

While such changes are intended to reduce greenhouse gas emissions and improve climate resiliency, they also have the potential to simultaneously improve building health given that many of the included measures overlap. This is especially the case for the reduction of particulate matter (i.e., PM2.5, PM10, and ultrafine particles), which is linked to heart attacks, asthma, and other adverse health effects (MacMunn, 2024). Data from NESCAUM suggests that just across the nine participating states, fossil fueled heating equipment releases approximately 138,000 tons of nitrogen oxides (NOx) and 6,000 tons of fine particulate matter, while buildings emit roughly 173 million metric tons of CO2 annually (MacMunn, 2024). When comparing a life cycle of a Minergie P home in Switzerland to a life cycle of a LEED Silver home in the United States, the Swiss home outperformed the latter in global warming potential, non-renewable energy consumption, and acidification, primarily a result of its use of a geothermal heat pump (Mosteiro-Romero et al., 2014). The replacement of fossil-fueled elements with their energy-efficient alternatives (e.g., heat pumps) indicates a potential to reduce both energy demand and subsequent pollutants. However, better understanding is needed of the beneficial relationship between heat pumps, low-VOC materials, and current pathways for improved human health.

Research Significance and Objectives

This research compared the benefits of retrofit homes that employ an energy-efficient heat pump and low-VOC materials, associated with the three distinct green building programs at the forefront of the sustainable building industry (i.e., LEED, Passive House, and WELL), on human health. The analysis offers a better assessment of the growing interest in health-forward buildings and the additional health benefits of nationwide building decarbonization. As society often can be hesitant to adopt sustainability initiatives, results may help architects and builders better develop building specifications that are more likely to benefit the occupant, thereby propelling the industry forward. Considering that 80% of buildings that will exist in 2050 are already built and the emphasis on retrofits in the Inflation Reduction Act, such a framework will impact the way in which homes are retrofitted with an eye toward energy and health (Grainger, 2022; *Inflation Reduction Act*, 2022).

Thus, my research objectives were:

- To discover whether energy-efficient features and low-VOC materials, included as options in the three green building programs (WELL, LEED, Passive House), result in measurable health impacts
- To contribute to existing literature on the health benefits of green buildings

- To provide suggestions on how to improve methodologies for evaluating building health

Background

Understanding what factors within the built environment influence the continuous rise of chronic illness is essential to slowing its rise. People spend over 90% of their time indoors and, while it varies from environment to environment, indoor air quality (IAQ) is often worse than outdoor air quality (Benefits of Green Buildings, 2023; Environmental Protection Agency, 2022). Diminished air quality has been linked to numerous health risks, which include coughing, wheezing, shortness of breath, cardiovascular diseases, respiratory diseases, asthma, cancers, and high rates of hospitalization (Manisalidis et al., 2020). On the other hand, improved IAQ is linked to higher productivity and cognitive functioning (Cedeño Laurent et al., 2021). Beyond air quality, other building attributes, such as building design (e.g., ventilation types and rates, filtration, access to natural lighting, biophilic properties), environmental risks (e.g., chemical and radiological hazards), and location and safety influence residents' mental and physical health (Bakó-Biró, 2012; Kim, 2015). Similarly, residents' behavior and activities throughout the lifetime of the building's operation (e.g., cleaning, maintenance, pest management, opening windows, use of non-toxic household products) are related to building occupant health and well-being (Adamkiewicz et al., 2014; Colton et al., 2014; Frumkin, 2003; Heschong et al., 2002; Tsoulou et al., 2023; Rosenfeld et al., 2011).

The following flowchart (Figure 1) represents the path through which I explore the existing literature with regard to green buildings and health. The corresponding numbers indicate the number of articles accessed associated with each category.

Numerous relevant studies were reviewed until saturation was reached regarding unique contributions on the topic. The highlighted articles/studies were chosen as they adequately summarized a majority of the findings and commentary on the subject.

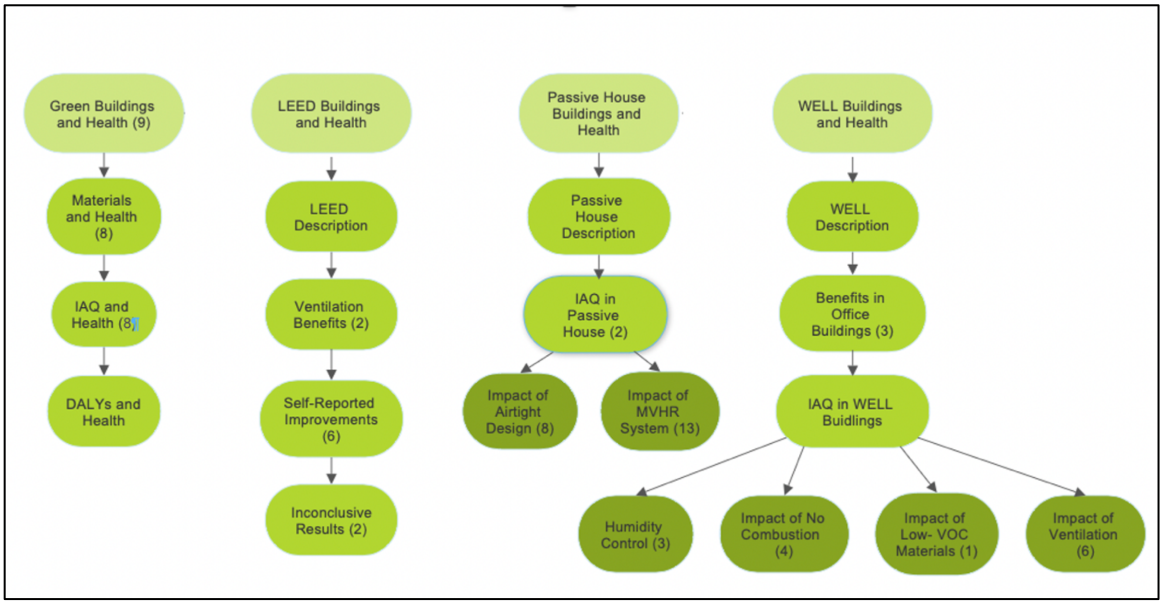


Figure 1. Flowchart- background topics and literature review.

Green Buildings and Health

As research continues to reveal a positive relationship between the built environment and well-being, there is a corresponding shift to adopt green buildings, not only for their energy efficiency, but also their health effects (PNNL, 2022). To reduce emissions and waste, energy and water use, reliance on natural resources, and impact on the natural environment, eco-friendly homes focus on optimal ventilation, lighting, thermal comfort, air quality, and water cleanliness (International Well Building Institute, 2023; LEED Rating Systems, 2023; Pacific Northwest National Laboratory, 2022;

Passive Building Principles, 2023). Therefore, these buildings incorporate a variety of strategic structural and technological aspects, such as quality air and water filtration systems, low VOC paint and low-emitting materials, access to natural lighting, renewable sources of energy, biophilic design, and inclusion of green space that may improve physical and mental health by limiting exposure to negative factors (e.g., harsh pollutants) and optimizing exposure to beneficial factors (e.g., sun exposure, plants) (International Well Building Institute, 2023; LEED Rating Systems, 2023; Pacific Northwest National Laboratory, 2022; Passive Building Principles, 2023).

While current research focuses primarily on the negative impacts of human health associated with conventional buildings, research that points to the beneficial implications of green buildings is still emerging; although often limited to case studies and self-reported data, measured data studies are increasing (Allen et al., 2015; Liu et al; 2023). Predicted or noted improvements include productivity, mental health, respiratory health, and overall well-being, among other measures. For example, occupants in public housing developments in Boston who moved into green homes experienced a reduction in sick building syndrome (SBS) symptoms by 47% (Colton et al., 2014). When occupant health in low-income housing was compared at baseline and a year later after green renovations, self-reports indicated significant improvements in overall health, general respiratory issues, and asthma for children and their parents (Breysse, et al., 2011). Furthermore, those who work in green buildings had a significant improvement in self-reported productivity and overall well-being, specifically as a result of improved air quality (Samet & Spengler, 2003).

What Qualifies as Healthy

Health has many definitions. While the term often refers to a lack of illness and injury, it can also indicate one's ability to cope with the demands of daily life or the balance between one and his social and physical environments (Sartorius, 2006). Therefore, health encompasses the well-being of both mind and body, including productivity or sociability (Sartorius, 2006).

A variety of factors may influence one's health. While genetics, education, employment status, and income play a definite role, other indicators linked to physical location, nutrition, and exercise are just as important (WHO Air Quality, Energy, and Health Team, 2023). With regard to building health, this means that passive properties, such as building materials and natural lighting, may have just as much an influence as active properties, such as what cleaning materials are used, on one's well-being (Bello et al., 2009; Kokulu & Ozgunler, 2019; Shishegar & Boubekri, 2016) .This range not only makes it difficult to understand which factors to prioritize, but also makes it challenging to pinpoint any one measurement that indicates improved health. Is a building that results in decreased risk of infection more or less beneficial than a building that results in improved mental health (Samet & Spengler, 2003)?

Materials and Health

One of the greatest influences on the health of a building is the quality of the built materials. Over the last century, with the dawn of the chemical revolution and modern additives, exposure to toxic pollutants has increased drastically, with double the amount of synthetic chemicals manufactured now than in 2000 (Naidu et al., 2021). While there are many alternative factors that impact exposure within a home (e.g., race, gender, age, socioeconomic status, cleaning activities, etc.) the fact that humans spend on average 90% of their time indoors, where chemical concentrations can be up to two times higher than outdoors, is an important consideration (US EPA, 2023a). Through off-gassing, photo-degradation, and abrasion, humans are exposed to toxic materials that may be invisible to the eye (Healthy Materials Lab, 2023). As a result, many chemicals are detectable in human bodies (i.e., flame retardant is found in all humans), and one in every 100 people develop a health problem related to the materials in their home (CDC, 2023c; Green Science Policy Institute, 2023b).

Consequences are not trivial; many conditions, such as cardiac diseases, diabetes, cancer, headaches, respiratory diseases, developmental changes in fetus, and mutations of genes, are a result of exposure to the six classes (i.e., PFAS, antimicrobials, flame retardants, bisphenols and phthalates, solvents and VOCs, and certain metal), as well as mold (Green Science Policy Institute, 2023a). Endocrine disruptors, such as PCBs in caulking or flame retardants found on couches, mimic estrogen and block testosterone actions at very low doses (Bayer et al., 2022; Roy et al., 2009). This can lead to subtle changes over long periods of exposure, such as metabolization issues, infertility, and thyroid hormone changes ((Boas et al., 2012; Roy et al., 2009; Rattan et al., 2017). Other toxins, like nanoparticles, which are found in most building materials (i.e., windows, steel, coatings, concrete) and are known to behave differently than their larger equivalents, are used at an increasingly high rate before their complete impacts on the environment and human health are fully understood (Kumah et al., 2023).

More sustainable options are not necessarily healthier. A recycled rug can be a product of a closed-loop system, but if it is an ortho-phthalate composed of PVC, it poses a risk to endocrine systems and development (Bayer et al., 2022). The reverse is also true. Some ingredients, such as chlorofluorocarbons, that are designed to minimize risk for human health can be harmful for the ozone and ecosystems (Badr et al., 1990). Therefore, a look at the entire life cycle of a material, as well as both its health and environmental impacts, is useful for understanding the best option for both a healthy and green building.

Unfortunately, toxic chemicals persist in homes due to a lack of transparency within the industry and the slow pace of federal regulation (Chiapella et al., 2019). It took almost 200 years for lead to be banned in paint, although its dangers were observed during the Industrial Era (CDC, 2023a). Similarly, when the United States Environmental Protection Agency (EPA) enacted the Toxic Substances Control Act (TSCA) in 1976, 62,000 chemicals were grandfathered into use, without data that reflected their accurate impact on health or the environment (Andrews, 2023). Untested new chemicals went straight to market, while tested chemicals meant that manufacturers had to supply information to the EPA; as a result, companies were more inclined to avoid testing (Andrews, 2023). The EPA was given 90 days to determine if a new chemical was safe to use, and those deemed potentially hazardous were voluntarily phased-out, rather than outright banned (Andrews, 2023). Forty years later, the EPA passed changes to the TSCA, allowing the EPA to have more power (Andrews, 2023; US EPA, 2023b). Now, they are able to request health & safety data sheets from manufacturers for existing and new chemicals and can question “confidential” or “trade secret” claims (Andrews, 2023; US EPA, 2023b). While their current goal is to review a list of ten chemicals of concern over the next five years, it leaves thousands of others still accessible without accurate review (Andrews, 2023; US EPA, 2023b).

Although required safety data sheets contain information about flammability and corrosive and biological properties of chemicals, specificity around potential impacts for the environment and human health are limited. Health Product Declarations aim to fix this discrepancy, but as a rather new type of reporting, they are not widely adopted across the industry (Vittori, 2023). Similarly, third party preparers and verifiers (e.g., Health Product Declaration Collaborative or Cradle to Cradle) that evaluate materials regarding their effect on health, the environment, and social welfare, assist manufacturers to create more detailed, reliable, and accurate data (Vittori, 2023).

IAQ and Health

The National Institute for Occupational Safety and Health (NIOSH) suggests that the safest means of creating a healthy home is to avoid any potentially toxic sources, but as evidenced, it is not so simple (CDC, 2023b). With multiple determinants of health and a lack of transparency within the material industry, it is difficult for consumers and designers to measure their progress, let alone reach a fully toxic-free home (Allen et al., 2015; Chiapella et al., 2019; Ige et al., 2019; Lui et.al., 2023). IAQ presents a realistic and objective measurement to better understand the relationship between building environment and health.

It is well documented that IAQ has a significant impact on one's well-being and quality of life (NIH, 2023). It is also suggested that there are greater health risks from daily indoor air pollution exposure than those from outdoor concentrations, especially for vulnerable populations (e.g., children or the elderly) (EPA, 2023c). Negative indoor pollutions can immediately irritate the nose, eyes, and throat; cause dizziness, headaches, or fatigue; or trigger other conditions, such as asthma (EPA, 2023c). Other effect may be long-term, showing up months or years after a period of exposure. These include a range of diseases, such as respiratory conditions, heart diseases, or cancer, which are potentially fatal (EPA, 2023c; Manisalidis et al., 2020). While the likelihood and extent of a reaction depends on a variety of factors (e.g., age, genetics, preexisting conditions), a home with a better IAQ may present a better opportunity for improved health (EPA, 2023c; Manisalidis et al., 2020).

Various chemicals impact IAQ. These include gases, such as carbon monoxide, ozone, and radon, particulate matter, volatile organic compounds, bacteria, fungi, pollen, fibers, and other organic and inorganic contaminants (EPA, 2023c). Such pollutants are a result of combustion (i.e., stoves, fireplaces, coal, tobacco products, or candles), emissions from the built environment (materials, furnishings, heating and cooling, humidification devices), outdoor pollutants, and occupant choices and behavior (i.e., smoking, cleaning products, painting, pets, tracking in and out of the home) (EPA, 2023c). Unfortunately, with persistent increased used of synthetic materials, personal care products, pesticides, and household cleaners in recent decades, indoor concentrations of air pollutants have increased, posing a potential risk for heightened levels of cardiovascular complications, respiratory diseases, endocrine disruptions, and other autoimmune disorders (EPA, 2023c). Limited ventilation, which results in a buildup of air pollutants, is linked to an increase in SBS, nausea, headaches, and decreased productivity (Allen, 2017; EPA, 2023a; Seppanen & Fisk, 2004; Sundell et al., 2011; Wargocki et al., 2002).

A relevant determinant on IAQ is human behavior. Tsoulou et al. (2023) highlighted several key findings regarding the impact of behaviors on indoor environmental conditions in senior public housing. Indoor heat index (HI) and PM2.5 levels significantly varied across the three apartment sites; the 1960's site experienced higher PM2.5 levels primarily a result of human behaviors, such as smoking and using candles/incense, while the 1930's site experienced higher HI levels most likely due to a poor envelope and lack of central air conditioning (Tsoulou et al., 2023). Differences in window opening patterns (i.e., which windows and when) resulted in varying impacts on IAQ (Tsoulou et al., 2023). For example, in approximately 20% of the samples, including some smoking units, opened windows benefitted IAQ and thermal comfort (Tsoulou et al., 2023). Nevertheless, in other instances, there was a trade-off between IAQ and thermal comfort, as opened windows in common spaces reduced indoor PM2.5 concentrations but increased indoor HI (Tsoulou et al., 2023). Alternatively, in some cases, opening of kitchen and living room windows led to nighttime cooling, but not reduce PM2.5 concentrations, particularly in units with smoking (Tsoulou et al., 2023). These findings emphasize that while natural ventilation has a significant effect on IAQ and thermal comfort, human behaviors, specifically smoking and window opening strategies, also have a relevant impact on IAQ alongside building design (Tsoulou et al., 2023).

Although studies have observed the health impacts of certain active factors, like occupant behavior and outdoor pollution, their variability from person to person and from one location to another makes them difficult to control when analyzing the health effects of a building (Luo et al., 2019). For this reason, only the impacts of factors unrelated to user behavior can be reliably studied.

DALYS and Health

Understanding the determinants of IAQ and its role in well-being helps define which factors to evaluate regarding health in the built environment. Nevertheless, using other forms of measurement, such as DALYs, might provide a new perspective to already existing research. In current research, DALYs are often used to compare the life expectancy and well-being of residents across different countries and are the primary calculation method in Health Impact Assessments.

As defined, one DALY represents the loss equivalent of one year of full health, a combination of years of healthy life lost die to premature mortality (YLLs) and years of healthy life lost due to sickness (YLDs) (World Health Organization, 2023). YLD includes the impact of different medical conditions; each is appointed a unique disability weight as a means to specify the intensity of the disability of the given disease (Salomon et al., 2015). Disability weights are amended as research about diseases continues to broaden (Salomon et al., 2015). While IAQ measurements indicate the quality of the environment that could be a potential cause of illness, DALYs highlight the years lost from illness.

The life cycle impact model, ReCiPe 2016, includes three "areas of protection" that encompass different impacts on health, the environment, and resource availability (Huijbregts et al., 2016). Sixteen different midpoint impact categories influence nine damage pathways; four of these (i.e., increase in respiratory disease, increase in various types of cancer, increase in other diseases/causes, and increase in malnutrition) are combined to calculate the damage to human health in terms of a DALY (Huijbregts et al., 2016) (Figure 2). Disability weights are typically linked to the onset probability of diseases that are influenced by relevant midpoint categories (e.g., Fine Particulate Matter Formation). These categories are related to the impact of the production and use stages across the LCA (Figure 2).

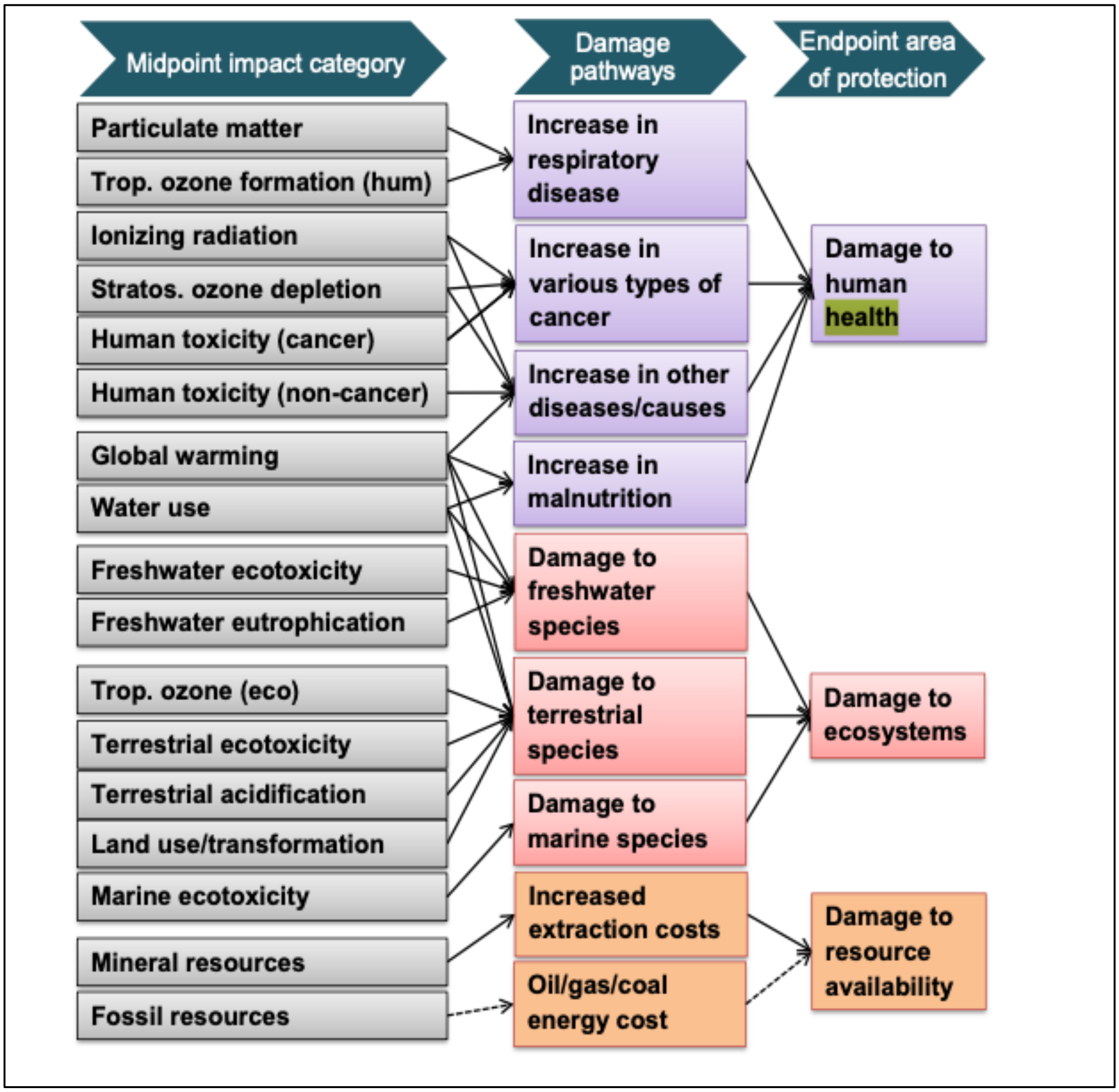


Figure 2. The impact categories included in the ReCiPe2016 methodology and their connection to damage to human health (Huijbregts et al., 2016).

LEED Buildings and Health

At the forefront of the industry are LEED Certified buildings, with over 45,630 certified buildings registered between 2017-2022 (Jhunjhunwala, 2022). LEED certification aims to reduce the sector's growing impact on climate change, protect water resources and biodiversity, utilize sustainable and regenerative materials, and benefit community quality of life and health (LEED Rating System, 2023). The certification requires that a building meets specific prerequisites regarding carbon, energy, water, waste, transportation, materials, health, and indoor environment. Buildings are awarded specific levels (i.e., Certified, Silver, Gold, Platinum) dependent on the number of the prerequisites met (LEED Credit Library, 2023).

Since buildings are certified by meeting a range of credits on the list, many LEED Certified buildings address energy and water conservation first, as the majority of credits impact these categories; only 20% of credits are associated with human health (LEED Rating System, 2023). Nevertheless, commonalities across the rating systems ensure that health is still considered in any certification level (LEED Rating System, 2023). Requirements include a minimum indoor air quality requirement, limited exposure to smoke, filtration, ventilation requirements, non-toxic and low-emitting paints and furnishings, healthy material choices, daylighting, and controlled pest management (Figure 1) (LEED Credit Library, 2023). To meet the highest level of certification, Platinum Certification, a building must adhere to perquisites and credits that total 80+ points.

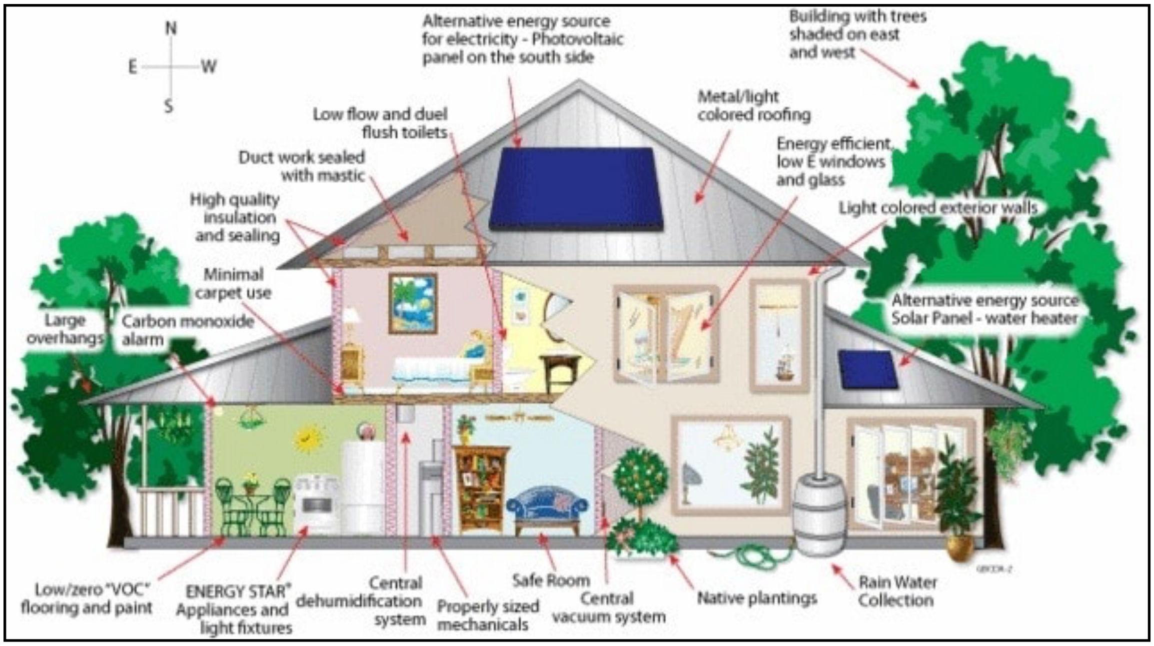


Figure 3. A hypothetical LEED Certified home (Fontan, 2020).

LEED factors that potentially impact improved health tend to focus primarily on superior air quality. For example, LEED Certified buildings had a statistically significant reduction in air quality pollution compared to their conventional counterparts, with reductions of approximately 50% in particulate matter (Phillips et al., 2020). As a result, researchers concluded that LEED buildings had a positive impact on occupants' respiratory health (Phillips et al., 2020). Similar improvements for those suffering with respiratory disorders were observed across numerous studies. For example, Garland et al. (2013) found that those who lived in a LEED Certified building had less continuous daily respiratory symptoms, disrupted sleep, and visits to an urgent healthcare center /professional for asthma.

Beyond respiratory improvements, Jacobs et al. (2014) found a significant improvement (i.e., 59% to 67%) in self-reported general health in adults when evaluating the difference between LEED Certified affordable housing and its counterpart in Washington D.C. Certain aspects utilized in LEED Certified buildings, such as regulated temperatures and improved air quality, resulted in occupant satisfaction and increased productivity in a workspace (Lee & Kim, 2008). Similar findings were recorded by Liang et al. (2014): there was a statistically significant difference between satisfaction of a green work building versus the conventional counterpart, with regard to thermal comfort, indoor air quality, acoustics, and lighting. Similarly, when a LEED Certified hospital was compared to the previous alternative, there was a 19% decrease in mortalities, as well as statistically significant improvements in staff satisfaction, productivity, and quality of care (Thiel et al., 2014). Enhanced indoor environment quality found in LEED Certified offices resulted in a decrease of "perceived absenteeism and work hours affected by asthma, respiratory allergies, depression, and stress," as well as self-reported productivity improvements (Singh et al., 2010). While satisfaction may seem unrelated to health, it is linked to improved mental health and decreased stress, factors that when not regulated can result in detrimental physical health consequences (Ohrnberger, 2017).

Not all studies evaluating the relationship between health and LEED buildings were as conclusive. For example, while those who worked in LEED Certified buildings saw self-reported improvements in overall health, performance, and satisfaction, many respondents also raised concerns about thermal conditions, lighting, noise, and design that negatively impacted productivity (Hedge et al., 2014). Likewise, Altomonte and Schiavon (2013) concluded that LEED certification and improved indoor environmental quality did not have a significant influence on occupant satisfaction; many residents were satisfied with the improved air quality but dissatisfied with lighting. Furnishing improvements, thermal comfort, indoor air quality increased productivity in LEED Certified workspaces, while lighting, acoustics, and layout changes positively influenced productivity in conventional buildings (Altomonte & Schiavon, 2013). Such findings suggest that LEED building design can be better refined to boost productivity and overall health of occupants. Or perhaps, that other green building programs, such as WELL or Passive House, might better benefit occupant health.

Passive House Buildings and Health

On the other end of the spectrum are Passive House buildings, which began in the 1970s as a way to create comfortable living spaces with high energy efficiency (Passive House Institute of the United States,2023a). While LEED Certified buildings must meet specific building requirements to attain certifications, Passive House buildings must meet energy, heating, and cooling thresholds, but are free to design and incorporate whatever building and architectural features are necessary to do so (Passive House Institute of the United States, 2023a). These features are taken from Passive House design, which presumes the following concepts: thermal bridge free design, efficient insulation, high-performance windows and doors, efficient ventilation systems with heat recovery, and airtight building envelope (Figure 4) (Passive House Institute of the United States, 2023a). While LEED and WELL emphasize technological improvements, Passive House focuses primarily on the “passive” structures in a building; therefore, typical improvements center around optimized insulation, windows, and ventilation systems (Passive House Institute of the United States, 2023a). According to PHIUS, the airtight building design, coupled with proper ventilation, maintains low indoor pollution levels, while limited drafts or excess humidity provide optimal comfort.

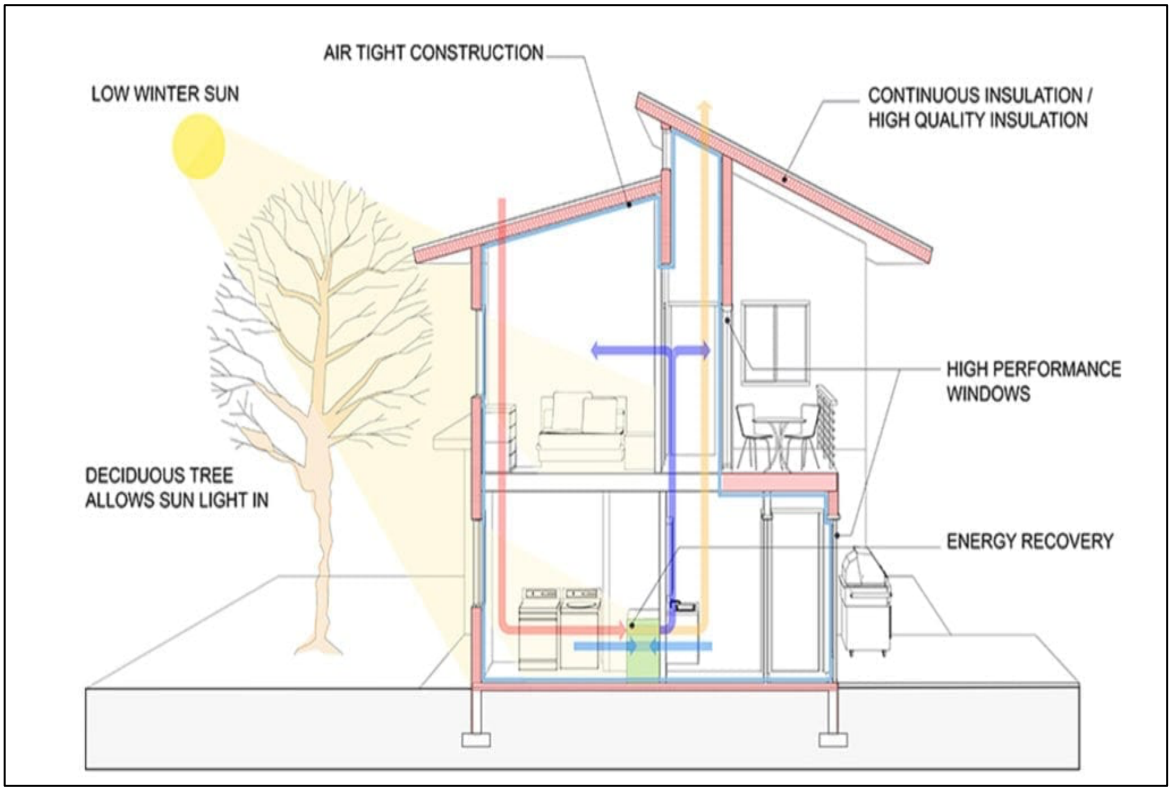


Figure 4. A hypothetical Passive House home- winter design (Mishra, 2020).

While there are limited studies that explore the relationship between Passive House buildings and health benefits, those that observe the relationship between IAQ and Passive House buildings are more prevalent, although they range in methods and results (Moreno-Rangel et al., 2020). Some evidence suggests that Passive House dwellings perform comparably if not better than other low-energy homes in terms of indoor air quality (Moreno-Rangel et al., 2020). Langer et al. (2015) found that particulate matter, VOCs, and formaldehyde were lower in passive dwellings. Nevertheless, research has indicated that proper maintenance of ventilation, filtration, and occupant education, as well as the fulfillment of mandatory certification thresholds are necessary for acceptable IAQ levels of Passive House homes (Moreno-Rangel et al., 2020)

Airtightness in Passive House homes provides energy conservation, as well as protection from water damage, cold air, and condensation (Schnieders & Hermelink, 2006). This prevention against potential outdoor pollutants, mold, and water damage may help to improve occupant health, yet studies are inconclusive, as there is evidence that air filtration might be either beneficial or detrimental to occupant health (Berge & Mathisen, 2015; Godish & Spengler, 1996; Less et al., 2015; Mendell, 1993; Moreno-Rangel et al., 2020; Seppanen et al., 1999). For example, Less et al. (2015) found that of 19 homes in California, those with higher levels of airtightness had the best IAQ and lowest levels of indoor air pollutants. Nevertheless, findings also suggested that practices, such as continuous ventilation and filtration, impacted IAQ levels (Less et al., 2015). Sherman & Chan (2004) suggest that without adequate ventilation, an airtight home can actually result in greater prevalence of indoor air pollutants. Therefore, to maintain safer levels of IAQ in airtight homes, ventilation should be prioritized (Moreno-Rangel et al., 2020).

Mechanical ventilation with heat recovery (MVHR) systems not only remove stale indoor air but replace it with filtered, fresh outdoor air (Brimblecombe & Rosemeier, 2017; Moreno-Rangel et al., 2020). Such systems are linked to a significant improvement in self-reported health compared to residents who lived in naturally ventilated homes (Wallner et al., 2017). This is in part due to Passive House homes' higher air exchange rates that result in lower levels of some VOCs, formaldehydes, and mold (Moreno-Rangel et al., 2020). Nevertheless, unless homes meet a ventilation rate above 0.5 ach-1, IAQ levels and/or occupant health might be affected (Dimitroulopoulou, 2012; Fischer et al., 2013; Spengler & Sexton, 1983). There is a higher likelihood of moisture, dust mites, and indoor pollutants that can exacerbate preexisting conditions, such as eczema or asthma, SBS symptoms, or reduced productivity (Dimitroulopoulou, 2012; Spengler & Sexton, 1983; Sundell et al., 201; Wargocki et al., 2002).

Similarly, MVHRs must be maintained properly and fitted with correct filters to protect the system from dust and other solid air pollutants; if incorrect filters are used, it can result in higher indoor air concentration levels of PM2.5 (Moreno-Rangel et al., 2020; Szirtesi et al., 2018). Incorrect interaction, understanding, and operation with the MVHR system, as well as occupant behaviors, such as opening windows, is also linked to MVHR misuse (Balvers et al., 2012). Balvers et al. (2012) found that of 150 homes with MVHR systems, 77% had dust in the ducts, 67% had dirt from material construction, 66% did not perform annual maintenance, and 43% had dirt in their homes. For this reason, proper guidance and installation can reduce potential operational issues (McGill et al., 2015). The variation across studies may be due in part to occupant behavior. When compared to pre-occupancy levels, homes showed increased levels of PM2.5, alkanes, benzene, and aldehydes temporarily after human activity, although immediate emissions from building materials may influence findings, as well (Derbez et al., 2014).

WELL Buildings and Health

While both LEED and Passive House incorporate health into an energy-focused criteria, a rather new and emerging building standard, WELL, places it at the forefront of their design standard (International Well Building Institute, 2023). With over 22,000 certified and rated buildings, WELL "applies the science of how physical and social environments affect human health, well-being, and performance" (International Well Building Institute, 2023, p. 2). It addresses 10 categories (i.e., air, thermal comfort, light, community, mind, movement, water, sound, materials, and nourishment) with a similar approach to LEED (International Well Building Institute, 2023). Buildings receive credits for each category by meeting specific requirements, some of which, such as quality filtration, clean water, and access to natural lighting, are also LEED requirements. WELL also includes criterion beyond that of LEED and Passive House, such as sleep quality factors, high quality carbon filtration, walkability, access to nutritious food, emphasis on biophilia (Figure 5), and limited chemical exposure (e.g., halogenated flame retardants, phthalates, and polyfluorinated chemicals) (International Well Building Institute, 2023). Platinum Certification, the highest level, is awarded when a building meets 23 mandatory WELL certification requirements, as well as 80% of 97 possible optimizations.

Figure 5. A WELL Certified building, EDGE Suedkreuz Berlin that utilizes biophilic design principles (WELL Press Team, 2018).

WELL buildings are becoming increasingly popular for office buildings. A transition to WELL Certified offices from conventional offices resulted in positive occupant satisfaction and statistically significant improvements in self-reported health, productivity, and well-being standards (Ildiri et al., 2022). This is also represented by higher ratings for overall satisfaction, productivity, health, and workability for WELL Certified buildings compared to the alternative (Candido et al., 2020). Similarly, relocation to a WELL Certified office resulted in a statistically significant positive increase in occupants' satisfaction, as well as insignificant, but still relevant, improvements in productivity and SBS symptoms (Licina & Yildirim, 2021).

Surprisingly, there is little to no research that explores the health effects of residential WELL certification. Nevertheless, as residential and commercial buildings follow the same guidelines, it can be inferred that such findings apply equally to residential homes, as well (WELL, 2023). In particular, the many requisites for indoor air quality are likely to support a healthier home environment (WELL, 2023). Humidity control and moisture management mitigate the potential for mold and bacterial growth, while protecting the building from pests or other damages (Arundel et al., 1986; Mudarri & Fisk, 2007; Stodola, 2019). Combustion minimization limits combustion sources (e.g., stoves and furnaces) that produce air pollutants, particularly carbon monoxide and methane (Stodola, 2019; WELL, 2023). Such pollutants are linked to respiratory diseases, fatigue, dizziness, and unconsciousness (California Air Resources Board, 2023). Construction pollution management requirements reduce fine and coarse particles during and immediately following construction; this aims to diminish the risk of associated respiratory ailments, including chronic obstructive pulmonary disease (COPD) (Sannolo et al., 2010; Singh et al., 2014; Stodola, 2019).

Low-emitting materials lessen VOCs that are linked to pulmonary diseases and related symptoms (EPA, 2023c; Stodola, 2019). Quality ventilation and filtration promote an “increased supply of high-quality air” that lowers risk of SBS, allergies, respiratory diseases, cardiovascular diseases, and other associated symptoms (Bräuner et al., 2008; Daisey et al., 2003; Stodola, 2019; Sublett, 2011; Wargocki et al., 2000). Furthermore, the WELL program rewards strategies that reduce the need for mechanical ventilation and supports the use of operable windows, as their research suggests that naturally ventilated buildings improve human experience and results in fewer reports of SBS (Burge et al., 1987; Stodola, 2019). Nevertheless, whether or not windows actually improve indoor air quality depends on both the pollutants in the outdoor air and the frequency of opened windows (EPA, 2023c). While criteria for cleaning products and smoke-free management address occupant behaviors, they are both necessary preconditions in WELL certification that ensure limited exposure to harmful chemicals (Stodola, 2019).

Lack of Comparison

Unfortunately, while it is highly suggested that green buildings influence positive health outcomes and there are studies that emphasize the health benefits of each green building program, no research has compared the three types in terms of their health impacts. The differences in construction and disparities between the three popular building standards suggests there are disadvantages or advantages to choosing one standard over the others. For instance, does the airtight structure of a Passive House home outweigh the benefits of cleaner materials and biophilic design in a WELL Certified building? Do the structural differences between the windows used in LEED Certified buildings and WELL Certified buildings play a role in overall health?

Addressing these questions is challenging goal to study for multiple reasons. As mentioned previously, numerous factors play a role in the health of a building, not all of which can be analyzed; healthy buildings require multidisciplinary thinking that integrates multiple resources across industries (e.g., architecture, product manufacturing, medical service, fitness) (Lui et al., 2023). Along with incomplete data regarding material toxicity, a life cycle analysis (LCA) does not directly incorporate aspects such as material toxicity and chemical composition that greatly impact IAQ and, therefore, health (Rey-Álvarez et al., 2022). Secondly, with many different permutations of a home that qualifies for each program, it is difficult to settle on a consistent and realistic model. Thirdly, it is challenging to hold constant other factors within the home when outdoor air quality and human behavior play such a significant role in building health (Adamkiewicz et al., 2014; Colton et al., 2014; EPA, 2023c; Frumkin, 2003; Heschong et al., 2002; Rosenfeld et al., 2011). As all three green building programs include perquisites that address human behavior, an LCA model that does not allow for behavioral inputs does not accurately represent the full impact of a building on health (U.S. Green Building Council, 2020; PHIUS, 2023; WELL, 2023). Similarly, because protocols and methods vary widely among case studies that investigate health, there is no unanimous measurement that accurately depicts results (Allen et al., 2015; Liu et al. 2023)

For this reason, rather than comparing three separate building models for each program, elements associated with the programs (i.e., heat pump and low-VOC materials) can be compared in terms of DALYs. This provides a better understanding of which factors within the three programs play a significant role in health and offers additional data to existing literature.

Program Comparison

I conducted a detailed review of the certification guidebooks to compare LEED, Passive House, and WELL programs in terms of 11 categories: Air Quality, Lighting and Energy, HVAC efficiency, Construction, Environment and Social Impact, Materials and Resources, Water Management, Site Location, Sanitation, Wellness, Food and Nourishment (Table 1). These categories were modified from those provided by *LEED & WELL Comparisons: Sustainably Building for Health & Wellness* (2023). Each category addressed specific subcategories and whether each program met requirements for that subcategory. As a result, I was able to differentiate programs based upon which categories and subcategories were most emphasized. A further layer of comparison was drawn between programs based upon which requirements were included within each of the subcategories.

Of the categories, six are unable to be analyzed in an LCA, as they pertain to human behavior and location, factors, as mentioned previously, that are unable to be held constant. These include Construction, Environmental and Social Impact, Site Location, Sanitation, Wellness, and Food and Nourishment. Of the remaining five, three categories (e.g., Air Quality, HVAC and Climate, and Materials and Resources) contain significant elements that differ between the programs, have the potential to impact health, and offer insight into the unique factors of each program.

Table 1. Green building program comparison across 11 categories.

Air Quality	**LEED**	**WELL**	**PASSIVE**
Advanced Air Purification	N/A	YES	YES
Air Flush	N/A	YES	NM
Air Filtration and Infiltration Management	YES	YES	YES
Enhanced IAQ Strategy	NFR	YES	NM
Environmental Tobacco Smoke Control/Smoking Ban	NFR	YES	NFR
Increased Ventilation/Ventilation Effectiveness	YES	YES	YES
IAQ Performance/Assessment	NFR	YES	NM
Air Quality Monitoring and Feedback	NFR	YES	NFR
Operable Windows	YES	YES	YES
Outdoor Air Systems	N/A	YES	N/A
VOC Reduction	YES	YES	YES
Air Tightness	N/A	N/A	YES
Combustion And Fireplace Safety	N/A	YES	YES
Energy Metering/Energy Efficient Interior Lighting Plan	YES	N/A	YES
Electrification Readiness	YES	N/A	YES

Lighting & Energy	LEED	WELL	PASSIVE
Automated Shading and Dimming Controls	NFR	YES	NM
Daylighting/Circadian Lighting Design	NFR	YES	YES
Light Pollution Reduction	NFR	N/A	YES
Energy Performance	YES	N/A	YES

Lighting & Energy	LEED	WELL	PASSIVE
Renewable Energy Production	YES	N/A	YES
Visual Lighting Design	N/A	YES	YES
High Performance Windows with Glazing	N/A	N/A	YES
Continuous Insulation	N/A	N/A	YES
Thermal Bridge Free Design	N/A	N/A	YES
Enhanced Refrigerant Management	NFR	N/A	N/A
HVAC & Climate	LEED	WELL	PASSIVE
Fundamental Refrigerant Management	YES	N/A	N/A
Humidity Control	N/A	YES	YES
Thermal Comfort	YES	N/A	YES
Construction	LEED	WELL	PASSIVE
Activity Pollution Prevention/Pollution Management	YES	YES	YES
Demolition, Excavation, Waste Management & Planning	YES	YES	N/A
IAQ Management Plan	NFR	YES	N/A
3rd Party On-Site Inspection and Quality Assurance	N/A	N/A	YES
Disaster Preparedness Planning	NFR	N/A	N/A
Environmental & Social Impact	LEED	WELL	PASSIVE
Green Power and Carbon Offsets	YES	N/A	YES
Green Vehicles Parking/Charging Stations	NFR	N/A	YES
Heat Island Reduction	YES	N/A	N/A
Social Equity	YES	N/A	N/A

Environmental & Social Impact	LEED	WELL	PASSIVE
Universal Accessibility	YES	N/A	N/A
Agricultural Contaminants Management	N/A	YES	N/A
Durability In Material Selection, Design & Operation	YES	N/A	YES
Enhanced Material Safety	NFR	YES	N/A
Environmental Product Declarations	NFR	N/A	N/A
Materials & Resources	LEED	WELL	PASSIVE
Organic + Inorganic Contaminants Management	N/A	YES	N/A
Low-Emitting Materials	YES	N/A	YES
Embodied Carbon / Low Carbon Material Ingredients	YES	N/A	YES
Station Life-Cycle Impact Reduction	YES	N/A	N/A
Sustainable Sourcing of Raw Materials	YES	N/A	YES
Building-Level Water Metering	YES	N/A	N/A
Cooling Tower Water Use	NFR	N/A	N/A
Drinking Water Promotion	N/A	YES	N/A
Water Management	LEED	WELL	PASSIVE
Indoor + Outdoor Water Use Reduction	YES	N/A	YES
Metering System	YES	N/A	YES
Periodic Water Quality Testing	N/A	YES	N/A
Public Water Additives	N/A	YES	N/A
Rainwater Management	YES	N/A	YES
Treatment Program	N/A	YES	N/A
Quality Views	YES	N/A	N/A

Water Management	LEED	WELL	PASSIVE
Reduced Parking Footprint	NFR	N/A	N/A
Sensitive Land Protection	YES	N/A	N/A
Site Location	LEED	WELL	PASSIVE
Site Assessment	YES	N/A	YES
Site Development - Protect or Restore Habitat	YES	N/A	N/A
Surrounding Density and Diverse Uses	YES	N/A	N/A
Sanitation	LEED	WELL	PASSIVE
Cleanable Environment	N/A	YES	N/A
Cleaning Equipment	N/A	YES	N/A
Cleaning Protocol	N/A	YES	N/A
Hand Washing Stations	N/A	YES	N/A
Healthy Entrance	N/A	YES	N/A
Microbe And Mold Control Plant	N/A	YES	N/A
Moisture Management	N/A	YES	YES
Pest Control	N/A	YES	N/A
Bicycle Facilities and Storage	YES	N/A	N/A
Wellness	LEED	WELL	PASSIVE
Integrative/Biophilia Design	N/A	YES	N/A
Physical Activity Spaces/Fitness Equipment	NFR	YES	N/A
Access To Nutritional Information	N/A	YES	N/A
Allergen Management	N/A	YES	N/A

Food & Nourishment	LEED	WELL	PASSIVE
Artificial Ingredients Reduction	N/A	YES	N/A
Contamination Management	N/A	YES	N/A

Yes = required for certification, NFR = not for residential, NM = not mandatory, N/A = not applicable.

While all three programs prioritize air quality design, the ways in which they do vary (Table 2). WELL incorporates advanced air filtration and purification, increased ventilation, a smoke-free environment, combustion management, and continual IAQ monitoring, LEED and Passive are more lax in their requirements, as many prerequisites are not required for their residential buildings (i.e., smoke-free buildings, IAQ monitoring) (Passive House Institute of the United States, 2023b; U.S. Green Building Council, 2020; WELL, 2023). The systems used for ventilation and filtration vary; WELL certification requires a MERV 13 filter or higher with a mechanical or natural ventilation system that meets ASHRAE requirements, LEED certification requires a MERV 8 filter or higher with options for local and whole house mechanical ventilation, Passive House homes require a MERV 13 filter with a mechanical ventilation and heat recovery system (Passive House Institute of the United States, 2023b; U.S. Green Building Council, 2020; WELL, 2023). Similarly, LEED and Passive programs prefer electric stoves, but not require combustion-free appliances, while WELL does (Passive House Institute of the United States, 2023b; U.S. Green Building Council, 2020; WELL, 2023).

While LEED and Passive house greatly emphasize quality HVAC systems and thermal comfort for their impact on environmental demand, WELL does not specify any requirements. LEED offers four types of heating, with different requirements for each system: Central AC, gas furnace, boiler, or heat pump (Passive House Institute of the United States, 2023b; U.S. Green Building Council, 2020; WELL, 2023). On the other hand, Passive House offers two non-combustion sources for heating: air source heat pump or ground source heat pump (Passive House Institute of the United States, 2023b). LEED certification requires Central AC ≥ 14 SEER OR ≥ 15 SEER, while Passive House must incorporate a MVHR system with 50% recovery (Passive House Institute of the United States, 2023b; U.S. Green Building Council, 2020).

Lastly, although low-emitting materials are touched on in all three programs, their requirements vary (Table 2). WELL places incredibly strict restrictions on materials and resources, in order to manage risk of asbestos, lead, PCB, heavy metals, flame retardants, formaldehyde, phthalates, and VOCs (WELL, 2023). Passive House requires that homes follow standards for EPA Indoor airPLUS Construction Specifications, which means that all composite wood, interior paints and finishes, hard surface flooring, carpet and carpet adhesives, carpet cushion, adhesives and sealants must be low-emitting (Passive House Institute of the United States, 2023b). LEED is less strict, requiring that 75% of paints and coatings, 75% of adhesives and sealants, 90% of flooring, 75% of wall panels, 90% of ceiling materials, 75% of insulation, 75% of furniture, 75% of composite wood are low-emitting (U.S. Green Building Council, 2020).

Table 2. Detailed aspects of each green building program

	LEED	WELL	PASSIVE
Air Filtration System	MERV) of 8+ for recirculating space conditioning systems. Must comply with ASHRAE 62.2–2016. Non-ducted systems do not need to follow MERV 8 requirements but must contain an internal air filter in the air-handling unit.	MERV 13 or higher	MERV 13 filter or higher and all exhaust air through a MERV 8 filter
Air Ventilation System	Local exhaust ventilation & whole house MV (120cfm requirement for 1690sqft)	Mechanical/natural ventilation system ASHRAE requirements	MVHR
Combustion	Preferred: electric stove. Combustion equipment allowed along with combustion venting.	Electric stove	Preferred: electric stove.
Cooling	Central AC: ≥ 14 seer or ≥ 15 seer	Not specified	MVHR (ERV) with 50% recovery
Window Performance	U- value: 0.22-0.26 for zone 4a	Operable windows – U value not specified	U value: 0.23 - 0.26 for zone 4a
Air Tightness	If an air filter home, must be airtight.	Airtight home envelope. Must comply with ASHRAE guideline 0-2005 & National Institute of Building Sciences guideline 3-2012.	0.06 cfm50 per square foot of enclosure

	LEED	WELL	PASSIVE
Moisture Design	Moisture-resistant backing materials in bathroom. Water-resistant flooring in bathroom, laundry room, kitchen, and spa. Water-resistant flooring within 3 ft of exterior doors. Drain and drain pan; drain with flow restrictor or automatic water shut-off. OR sloped floor for tank water heater. Braided washer hose or drain and drain pan; drain pan and automatic water shut-off or flow restrictor; or floor drain with sloped floor for laundry machine. Exhaust outdoors for laundry dryer. No water leaks in plumbing.	Building envelope minimizes moisture intrusion and accumulation. Condensation and liquid water management using moisture-sensitive and moisture-resistant materials. Water leak control in fixtures using accessible shut-off connections. Water treatment devices have a backflow prevention system. Annual scheduled inspection for water damage, mold, water pipe leak, etc.	Detailed plans for site/foundation, walls/roofs, building materials.
Heating	Central AC: ≥ 10 hspf or ≥ 10.5 hspf. Gas furnace: ≥ 92 AFUE or ≥ 94 AFUE. Boiler: ≥ 87 AFUE or ≥ 90 AFUE. Heat pump.	Not specified	Air source heat pump: Cop @ 5f≥ 1.75 Seer ≥ 15 Ground source heat pump: Cop ≥ 3.1 EER ≥16.1
Vehicles	None	None	EV Charger
Appliances	One must be Energy Star: Refrigerator, dishwasher, clothes washer.	Not specified	Refrigeration, dishwasher, and clothes washer are Energy Star qualified.

	LEED	WELL	PASSIVE
Low-Emitting Materials	75% of paints and coatings, 75% of adhesives and sealants, 90% of flooring, 75% of wall panels, 90% of ceiling materials, 75% of insulation, 75% of furniture, 75% of composite wood.	Manage asbestos, lead, PCB, heavy metal hazards. Control over flame retardants, formaldehyde, phthalates. Low-emitting furniture and furnishings, flooring and insulation, adhesives, sealants, paints, and coatings.	Low-emitting composite wood, interior paints and finishes, hard surface flooring, carpet and carpet adhesives, carpet cushion, adhesives and sealants.

Focusing on Retrofits to Older Homes

With 80% of homes that will exist in 2050 already built, it is crucial to evaluate the current building stock to offer improvements where it lacks (Grainger, 2022). As of now, the ageing housing stock does not meet the energy or health demands that is necessary to support a more sustainable future. The residential sector accounts for approximately 21% of America's energy consumption, with homes built before 1950 using 40% more energy than those built after 2000 (Bardhan et al., 2014). Unfortunately, a large majority of America's building stock is older, with approximately 51% of single-family homes built before 1980 (Where is the aging, 2023).

This trend is also reflected in the State of New Jersey, with 40% of homes built during or before the 1950's (ResStock, 2022). Thus, it can be logically inferred that the majority of homes in the state have sub-standard energy performances. For this reason, a focus on retrofits, as improvements to the already existing and sub-par housing stock, will boost energy performance across the industry and help meet environmental goals for 2050.

Research Question, Hypotheses, and Specific Aims

The previous sections lead logically to my main research questions: Are there "green aspects" within the three popular building programs that result in improved health benefits? Do any of the elements offer greater benefits than the alternatives? Can results further inform on the health benefits of particular green building programs for retrofit homes? The business-as-usual model (BAU) model I created in an LCA was a hypothetical 1970's vintage one-story home that is then upgraded to two different versions of a greener home, each with prominent aspects found across LEED, Passive House, and WELL certified residential buildings in order to evaluate the following hypotheses:

- H1: A retrofit of a conventionally built home that incorporates green building elements will result in a greater improvement (decrease) in Disability Adjusted Life Years (DALYs) compared to a conventional building approach.
- H2: Incorporation specifically of low-VOC materials will result in the greatest improvement (decrease) in DALYS relative to the conventional build and the incorporation of an energy-efficient heat pump.

Specific Aims

To complete my research, I:

1. Compared LEED, WELL, and Passive House programs according to their guidebooks, across 11 categories.
2. Created a hypothetical Conventional Model that complied with the building codes of its time and NJ housing stock data.

3. Conducted an LCA to analyze its impact on health, in terms of DALYs, across a 20-year lifetime of the building, based on the predicted lifetime of a heat pump.
4. Amended the materials and quantities for the Conventional Model according to the guidelines outlined by the programs to create a Low-VOC Model and an Energy-Efficient Model.
5. Conducted an LCA to analyze these models' impact on health, in terms of DALYs, across a 20-year lifetime as a means to determine whether such upgrades improved well-being as a result of reduced exposure to environmental health hazards.
6. Scaled results to study the impact on a greater scale and ran a Monte Carlo Uncertainty Analysis to evaluate uncertainty about the effectiveness of a heat pump on human well-being.
7. Conducted sensitivity analyses that considered bamboo and hardwood flooring options, as well as a combination of low-VOC materials and a heat pump, to see if changes impact results.
8. Provided evidence-based recommendations to improve research practices that optimize understanding of occupant health and well-being, based on the LCA.

Chapter II

Methods

To better understand the relationship between sustainable building features and well-being, I conducted an LCA in SimaPro to evaluate the health impacts, in terms of DALYs, associated with the transition from a Conventional Model to (1) a Low-VOC Model and (2) an Energy-Efficient Model that utilizes a heat pump. While past research methods have relied primarily on occupant surveys or indoor air quality measurements to determine health effects of a building, I constrained this analysis to the buildings' materials and mechanicals. I did not attempt to model building occupant behavior, as there is an inability to know the behaviors of any given building occupant, including those that may have a direct impact on building health (e.g., those that impact indoor air quality, such as tracking, smoking, cooking, burning fires and candles, methods of cleaning).

The LCA complied with ISO 14040 and 14044, which outline necessary requirements to conduct a complete building LCA: goal and scope, life cycle inventory analysis, life cycle impact assessment, life cycle interpretation, reporting and review, limitations, relationships between LCA phases, and conditions for values and elements.

LEED, WELL, and Passive House programs were compared according to their guidebooks to determine important green building features to evaluate (Table 1). A Conventional Model home was constructed based upon NJ housing stock data. It was modified to incorporate low-VOC materials or an air-source heat pump, green building elements associated with LEED v4.1 Certified, WELL v2 Certified, and Passive House Institute (i) 10.B guidelines. Materials quantities and energy demands were compiled into an inventory and input into Simapro using Ecoinvent, USLCI, and US-EI 2.2 data. The Conventional Model was compared to the Low-VOC Model and the Energy-Efficient Model using ReCiPe 2016 endpoint methodology. Health impacts were represented as DALYs and scaled to represent between 7-40% of the New Jersey housing stock. Three sensitivity analyses were run: a Low-VOC Model with bamboo flooring, a Low-VOC Model with hardwood flooring, and a Combo Model with low-VOC materials a heat pump.

SimaPro

The base inventory and subsequent changes were made in SimaPro, the industry-leading software for conducting LCAs, and utilized data from the Ecoinvent Database, the U.S. Life Cycle Inventory Database, and the US-EI 2.2. Database. Inputs represented the impacts of production and use for each material and process across the LCA in DALYs.

I chose to employ SimaPro because it provides the most comprehensive options for inputs, including options for materials, heating, and more. Additionally, it includes the ReCiPe 2016 methodology that calculates in DALYs, allowing for a health analysis.

DALYs

There is not a universal metric to evaluate the health of buildings that efficiently considers all influencing factors, which makes it difficult to compare the three building standards (Liu et al., 2023). Nevertheless, DALYs, which represents the equivalent loss of one year of optimal health, is often used to record the impact on human health. Therefore, all models were compared in terms of DALYs, which represents the loss equivalent of one year of full health. It is calculated by combining the potential years of healthy life lost die to premature mortality (YLLs) with years of healthy life lost due to sickness (YLDs) (World Health Organization, 2023). In my DALYs calculations, years lost due to premature mortality or sickness were endpoints that resulted primarily from the midpoints accounted for in the ReCiPe 2016 method: Global Warming, Human Health; Stratospheric Ozone Depletion; Ionizing Radiation; Ozone Formation, Human Health; Fine Particulate Matter Formation (Huijbregts et al., 2016).

Scope and System Boundaries

The Conventional Model was modeled as a 1970's vintage home located in New Jersey, USA that complied with the building codes of the time. The Low-VOC Model, the Energy-Efficient Model, and the three models tested in the sensitivity analyses incorporated green building elements associated with LEED v4.1 Certified, WELL v2 Certified, and Passive House Institute (i) 10.B guidelines. The functional unit studied was one 1,690 square foot home, and the life service period of all models was 20 years, the approximate lifetime of a heat pump. Data were amended to accurately represent the material needs, upgrades, and energy demands over this time period.

The LCA focused on the related health impacts, in terms of DALYs, across the production and use stage of the home's lifetime (Figure 4). The analysis excluded other stages, as it aimed to study only the impacts of a home's physical structure and mechanicals on human health (Figure 6). Therefore, it was important to consider the manufacturing of the materials, as well as the energy demands during the home's use.

While construction and end-of-life are related, they do not directly highlight the effects of the physical materials and their relationship with users; for this reason, they were excluded.

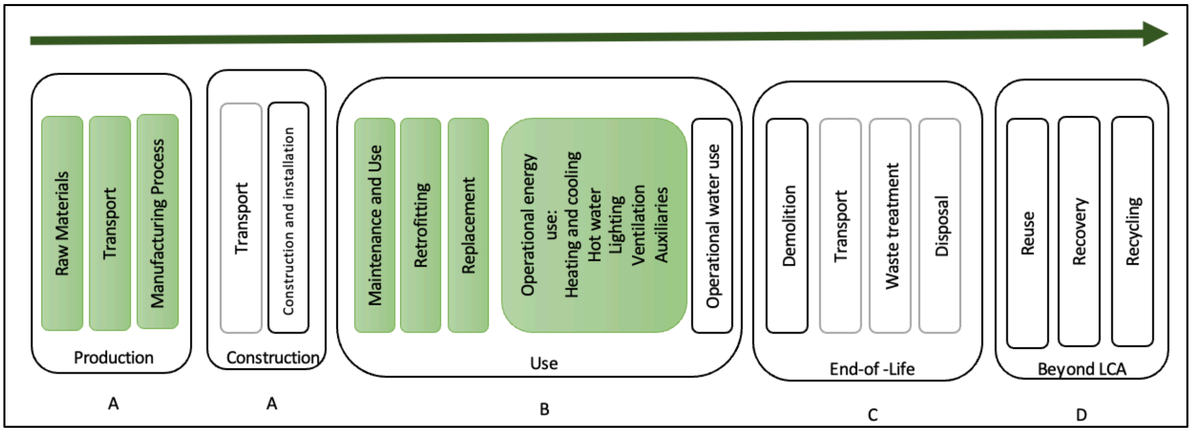


Figure 6. System boundary diagram.

Green indicates stages that were explored.

Conventional Model

The characteristics of the Conventional Model were compiled through research on the New Jersey housing stock. NJ's building code was first drafted in 1968, so the 1970's, the third most prevalent vintage in New Jersey, was chosen for the Conventional Model (Department of Community Affairs, 1968; ResStock, 2022). Data from the ResStock Metadata 2022 informed which aspects were incorporated into the Conventional Model. The most prevalent features of single-family 1970 residential homes in NJ were combined to represent approximately 7% of the NJ stock.

Within the 1970s vintage, single-family detached one-story homes located in climate zone 4A were the most common. Other attributes found across most 1970s vintage homes, and included in the model, were uninsulated slab foundation, wood framing, natural gas and ducted heating, and an HVAC system with a furnace (80% AFUE) and central air conditioning unit (SEER 13.0). The model's windows were clad-wood frames, double pane, with no glazing or coating. The frame was composed of wood studs with expanded polystyrene foam (EPS) insulation, as well as eight-foot ceilings with an uninsulated vented attic. Roofing material was asphalt. Other details of the home were collected based on the building code for the time. These included a polystyrene house-wrap, plywood sheathing and decking, ½ inch gypsum board drywall, and hollow core wood doors. Flooring (i.e., ceramic tile, carpet, and laminate) were based on trends and upgrades over the years but were consistent with the building code demands.

The Low-VOC Model and the Energy-Efficient Model

The sustainable building elements that served as the basis for the Low-VOC Model and Energy-Efficient Model were determined through research of the LEED, WELL, and Passive House certification guidebooks. As the models represented a partial retrofit design of the Conventional Model, not all materials were updated to comply with certification guidelines. Rather, I compared the three green building programs across 11 categories (Table 1): Air Quality, Lighting and Energy, HVAC Efficiency, Construction, Environment and Social Impact, Materials and Resources, Water Management, Site Location, Sanitation, Wellness, Food and Nourishment. I highlighted whether each program addressed specific sustainable initiatives and design elements (e.g., electrification readiness, low-emitting materials, high performance windows) and indicated which elements each program employs to address these initiatives (e.g., MERV 13 filters, energy star appliances) (Table 2).

As a result, I highlighted two prominent green building elements that were observed across the three models and were plausible upgrades for homeowners. These included homes with low-emitting materials and homes with energy-efficient heating, specifically a heat pump. Within the category of low-emitting materials, I chose to specifically focus on low-VOC materials, as VOCs are the most common contaminant in indoor air aside from particulate matter, can be up to ten times higher indoors than outdoors, and are associated with a range of health risks (US EPA, 2023d). Common VOCs include formaldehyde, benzene, methylene chloride, ethylene glycol, and xylene (Environmental Working Group, 2024; US EPA, 2023d).

The Low-VOC Model differed from the Conventional Model in three areas. A traditional acrylic paint was replaced with a water-based non-toxic alternative, modeled after the eco-friendly brand ECOS paint. Data were collected from the Safety Data Sheet and ingredients list located on the website, as well as discussion with the manufacturers. The carpet and wood laminate floorings were replaced with a low-VOC wood flooring throughout the home that substitutes a formaldehyde resin for a soy-based one. Lastly, while EPS insulation is less toxic than alternatives, it was replaced with cellulose insulation, the chosen insulation for WELL and Passive Homes.

The Energy-Efficient Model differed from the Conventional Model in its heating and cooling source. Rather than a traditional furnace, this model featured an air-source heat pump with a heating efficiency of 330% and a cooling efficiency of SEER 15.

While LEED, Passive House, and WELL programs vary in ventilation requirements, I did not include different ventilation systems within the comparison in the LCA for the following reasons. Firstly, I did not consider installing a MVHR as a plausible upgrade for most homeowners, unless they also upgrade the structure of the home to make it airtight. Without the costly and time-consuming renovation to convert a home to airtight, a MVHR would work overtime to account for the heat lost and excess pollution, results of thermal bridges and structural gaps. In such a scenario, it would possibly require more energy to properly ventilate a home than a traditional system. Additionally, an LCA evaluates the effects of a ventilation system's production and energy demand on DALYs, but not its filtering capabilities. While the former is important, the results would not differ drastically from a traditional ventilation system, as their production requirements and energy demands are similar. Rather, a MVHR impacts health the most, and differs greatly from a traditional ventilation system, in its effectiveness to filter air and keep healthy levels circulating in airtight homes. As an LCA cannot evaluate IAQ or ventilation effectiveness, its inclusion in the study would not be very informative.

Inventory

The inventory included mostly passive products, or those that are fixed in the building: structural materials (e.g., concrete, plaster, insulation) and finishing items (e.g., paint, polishes). These highly impact indoor air quality, with long-term emissions that taper over time (Wu & Apul, 2015). Active products include items that are incorporated in the home and are operated often, impacting indoor air quality but primarily during operation (Wu & Apul, 2015). As mentioned previously, I did not account for operational activities of occupants, as there is an inability to know their exact behaviors. These refer to cleaning products, pets, smoking, tracking, and window use that might have a direct impact on indoor air quality and subsequent health effects. In particular, the choice to exclude window use was based on the knowledge that in any high-performance building that prioritizes ventilation, it is critical to have as much control over air quality as possible. Keeping windows closed limits potential negative outdoor exposures.

To initiate the LCA, a rough blueprint of the Conventional Model was drawn as guide for material needs and estimations (Figure 7). The home characteristics were input into Athena Impact Estimator, a free software tool to evaluate buildings according to LCA methodology. Based on the location and design requirements, it produced an accurate list of building material and process quantities for the Conventional Model. These values were supplemented by a local New Jersey contractor, active in the New Jersey housing stock, and based on the New Jersey building code and requirements. The complete list of values is found below (Table 3).

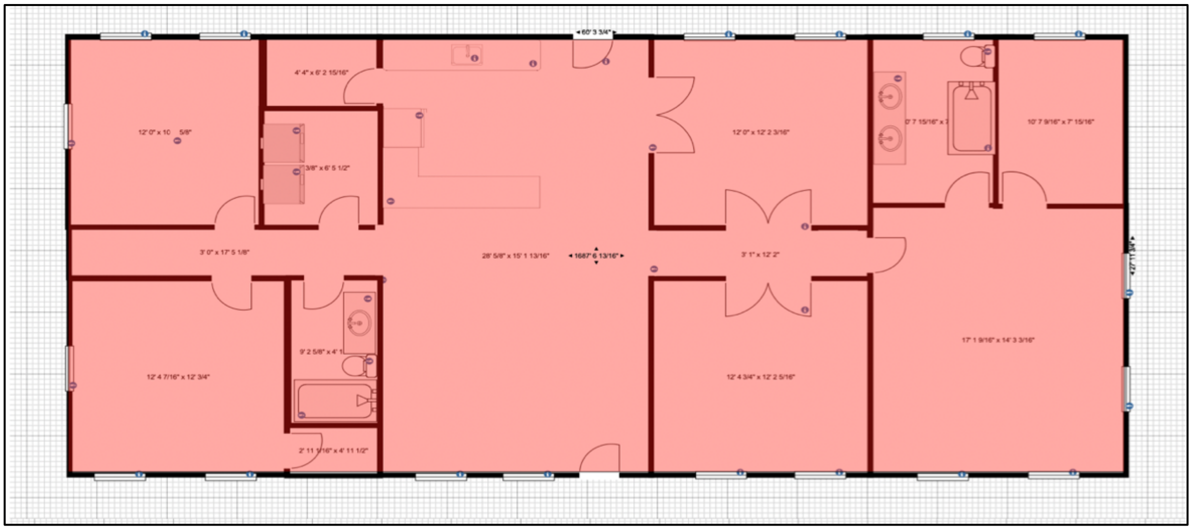


Figure 7. Blueprint layout of the Conventional Model.

Table 3. Material quantities from Athena Impact Estimator and NJ contractor.

Material	Unit	Total Qty.	Beams	Floors	Foundation	Roof (x2)	Walls	HVAC	Mass Value	Mass Unit
#15 Organic Felt	100sf	47.88	0.00	0.00	0.00	47.88	0.00	0.00	0.3579	Tons (short)
1/2" Moisture Resistant Gypsum Board	sf	2824.80	0.00	0.00	0.00	0.00	2824.80	0.00	2.6064	Tons (short)
3 mil Polyethylene	sf	1343.68	0.00	0.00	0.00	0.00	1343.68	0.00	0.0103	Tons (short)
Concrete Benchmark USA 3000 psi	yd3	22.56	0.00	0.00	22.56	0.00	0.00	0.00	43.5994	Tons (short)
Double Glazed No Coating Air (x3)	sf	285.27	0.00	0.00	0.00	0.00	285.27	0.00	0.4731	Tons (short)
Expanded Polystyrene	sf (1")	5434.50	0.00	0.00	0.00	0.00	5434.50	0.00	0.4007	Tons (short)
Galvanized Sheet	Tons (short)	0.22	0.00	0.03	0.00	0.19	0.00	0.00	0.22	Tons (short)

Material	Unit	Total Qty.	Beams	Floors	Foundation	Roof (x2)	Walls	HVAC	Mass Value	Mass Unit
Glass Fibre (x3)	lbs	289.36	0.00	0.00	0.00	0.00	289.36	0.00	0.1447	Tons (short)
Laminated Veneer Lumber	ft3	4.90	0.00	0.00	0.00	0.00	4.90	0.00	0.07	Tons (short)
Large Dimension Softwood Lumber, kiln-dried	Mbfm large dim.	2.40	0.00	2.40	0.00	0.00	0.00	0.00	1.8272	Tons (short)
Organic Felt shingles 20yr	100sf	58.80	0.00	0.00	0.00	58.80	0.00	0.00	6.3113	Tons (short)
Small Dimension Softwood Lumber, kiln-dried	Mbfm small dim.	4.69	0.00	0.00	0.00	2.19	2.50	0.00	3.3865	Tons (short)
Softwood Plywood	msf (3/8")	8.62	0.00	2.81	0.00	2.23	3.59	0.00	4.0119	Tons (short)
Vinyl Clad Wood Wndw Frame (x2)	lbs	728.06	0.00	0.00	0.00	0.00	728.06	0.00	0.364	Tons (short)

Material	Unit	Total Qty.	Beams	Floors	Foundation	Roof (x2)	Walls	HVAC	Mass Value	Mass Unit
Water Based Acrylic Paint	Gal. (us)	74.57	0.00	0.00	0.00	0.00	74.57	0.00	0.2334	Tons (short)
Welded Wire Mesh / Ladder Wire	Tons (short)	0.16	0.00	0.00	0.16	0.00	0.00	0.00	0.1638	Tons (short)
Ceramic tile	lb	450.00	0.00	300.00	0.00	0.00	405.00	0.00	X	Tons (short)
Cement backer board	lb	400.00	0.00	250.00	0.00	0.00	353.25	0.00	X	Tons (short)
Mortar	lbs	50.00	0.00	38.00	0.00	0.00	12.00	0.00	X	Tons (short)
Wood Flooring	sqft	900.00	0.00	900.00	0.00	0.00	0.00	0.00	X	Tons (short)
Carpet (x3)	yards	70.00	0.00	70.00	0.00	0.00	0.00	0.00	X	Tons (short)
Furnace (x2)	Prod.	1.00	0.00	0.00	0.00	0.00	0.00	1.00	X	Tons (short)
Ventilation system (x3)	Prod.	1.00	0.00	0.00	0.00	0.00	0.00	1.00	X	Tons (short)
AC system (x2)	Prod.	1.00	0.00	0.00	0.00	0.00	0.00	1.00	X	Tons (short)

Material	Unit	Total Qty.	Beams	Floors	Foundation	Roof (x2)	Walls	HVAC	Mass Value	Mass Unit
Heat pump (x2)	Prod.	1.00	0.00	0.00	0.00	0.00	0.00	1.00	X	Tons (short)
Non-toxic wood flooring	Cuft	70.00	0.00	70.00	0.00	0.00	0.00	0.00	X	Tons (short)
Cellulose insulation	Tons	0.40	0.00	0.00	0.00	0.00	0.00	0.00	0.4003	Tons (short)
ECOS paint (x 10)	Gal. (us)	74.57	0.00	0.00	0.00	0.00	74.57	0.00	0.2334	Tons (short)

Green indicates materials only included in the retrofit models.

To input these values into SimaPro, Ecoinvent, USLCI, and US-EI 2.2, data were matched to the materials and processes output by Athena Impact Estimator (Table 9, Appendix 1). Data were categorized according to structures, and assemblies were built for walls, roofing, flooring, doors, and HVAC systems. Some data were modified to realistically portray the Conventional Model. For example, the ventilation system was resized from a 703m2 apartment building to that for a 157m2 home (i.e., ≈1690 sq.ft). For those items with no equivalent data in SimaPro, assemblies were built according to manufacturer data. These include the carpet, low-VOC paint, low-VOC flooring, and the traditional HVAC system (Table 9, Appendix 1).

Energy demand for the Conventional Model was calculated based on ResStock data. The average energy demand for a 1970s home was 36,968 kBTU for lighting, 30,622 kBTU for equipment, 36,187 kBTU for heating, and 3,716 kBTU for cooling. Nevertheless, these numbers were based on homes with an efficiency of AFUE 72% and cooling demand with an efficiency of SEER 10. The ResStock Data suggested that the average efficiency for heating and cooling of 1970's, single-family, detached homes was AFUE 80% and SEER 14, respectively.

Therefore, I scaled the demand to AFUE 80% and SEER 14 by multiplying by the average demand by the difference (Table 4). Similarly, to calculate the demand for the Energy-Efficient Model, I scaled the demand for a heat pump with a heating efficiency of AFUE 330% and a cooling efficiency of SEER 15 by multiplying by the difference. Final energy demands are represented in the table below (Table 4).

Table 4. Energy requirements for the Conventional Model and the Energy-Efficient Model.

Energy Consumption: Conventional Model	Consumption in (kBTU)
Heating (AFUE 80%)	3165.98275
Cooling (SEER 14)	2654.34999998
Equipment	30,622.12
Lighting	36,967.70

Energy Consumption: Energy-Efficient Model	Consumption in (kBTU)
Heating (AFUE 80%)	3165.98275
Cooling (SEER 14)	2654.34999998
Equipment	30,622.12
Lighting	36,967.70

Procedure and Scaling

The ReCiPe 2016 endpoint methodology was employed to compare the Low-VOC Model, the Energy-Efficient Model, and the Conventional Model. Primary midpoints addressed include: Global Warming, Human Health; Stratospheric Ozone Depletion; Ionizing Radiation; Ozone Formation, Human Health; Fine Particulate Matter Formation (Huijbregts et al., 2016). Less relevant midpoints addressed include: Human Carcinogenic Toxicity; Human Non-carcinogenic Toxicity; Water Consumption, Human Health (Huijbregts et al., 2016). Health Impacts were represented as DALYs. Findings were scaled to represent 7%, 10%, 15%, 20%, 25%, 30%, 35%, and 40% of the NJ housing stock to illustrate the impact sustainable building elements could have across a state-wide scale. 13% of the NJ housing stock was of the 1970's vintage (i.e.,1,895 homes). Of this, 7% of the housing stock represented the total number of 1970's vintage, single-family detached homes in NJ (i.e., 1,035 homes). 15%- 40% indicated homes beyond the 1970's vintage, therefore, results may suggest possible similar impacts for the remaining homes in NJ, especially those with vintages older than the 1970's.

A Monte Carlo Uncertainty Assessment was also run to determine if the heat pump used in the Energy-Efficient Model seemed a beneficial upgrade to a conventional home. The Conventional Model was tested against the Energy-Efficient Model over 400 times to create a larger sample size. According to the SimaPro manual, "the different samples [were] chosen in such a way that all samples together [conformed] to the distribution specificized in the data" (Goedkoop et al., 2016, p. 84).

Sensitivity Analyses

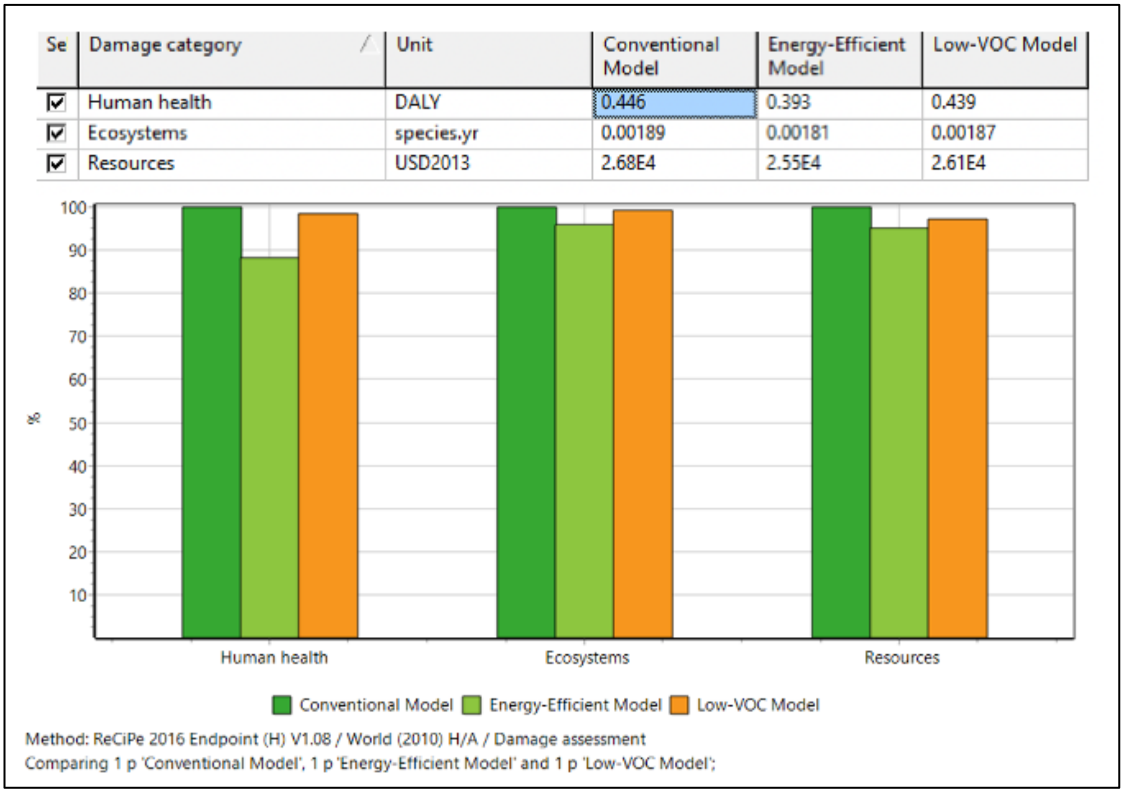
Finally, I conducted a sensitivity analysis to account for low-VOC bamboo flooring and low-VOC hardwood flooring, in addition to the engineered low-VOC wood flooring in the Low-VOC Model. Bamboo is a popular, eco-friendly flooring option, as it is more durable than traditional wood floors, lasts longer, and grows quickly and abundantly. Solid hardwood floors are similarly durable and are often considered the healthiest option for flooring, with low to zero VOCs.

To conduct the sensitivity analysis, I replaced the input for the low-VOC flooring (e.g., glued laminated timber) with inputs for a low-VOC hardwood flooring (e.g., glued solid hardwood timber) and inputs for a low-VOC bamboo flooring (e.g., glued laminated bamboo) (Table 4).

Chapter III

Results

The primary results are displayed in Figure 8, calculated with the ReCiPe 2016 Endpoint method. The Conventional Model resulted in ≈ 0.446 DALYs, the Low-VOC Model resulted in ≈ 0.439 DALYs, and the Energy-Efficient Model resulted in ≈ 0.393 DALYs over a twenty-year lifetime, the approximate life span of a heat pump.



Se	Damage category	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model
☑	Human health	DALY	0.446	0.393	0.439
☑	Ecosystems	species.yr	0.00189	0.00181	0.00187
☑	Resources	USD2013	2.68E4	2.55E4	2.61E4

Method: ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A / Damage assessment
Comparing 1 p 'Conventional Model', 1 p 'Energy-Efficient Model' and 1 p 'Low-VOC Model';

Figure 8. Results for human health (DALYs), ecosystems, and resources across all three models.

The y-axis is percentage of units (i.e., DALY, species.yr, USD2013) produced by the Conventional Model.

When normalized, as to allow all three impact categories to be compared with the same unit, findings suggested that all three models had the greatest influence on Human Health, even more so than Ecosystems (Figure 9).

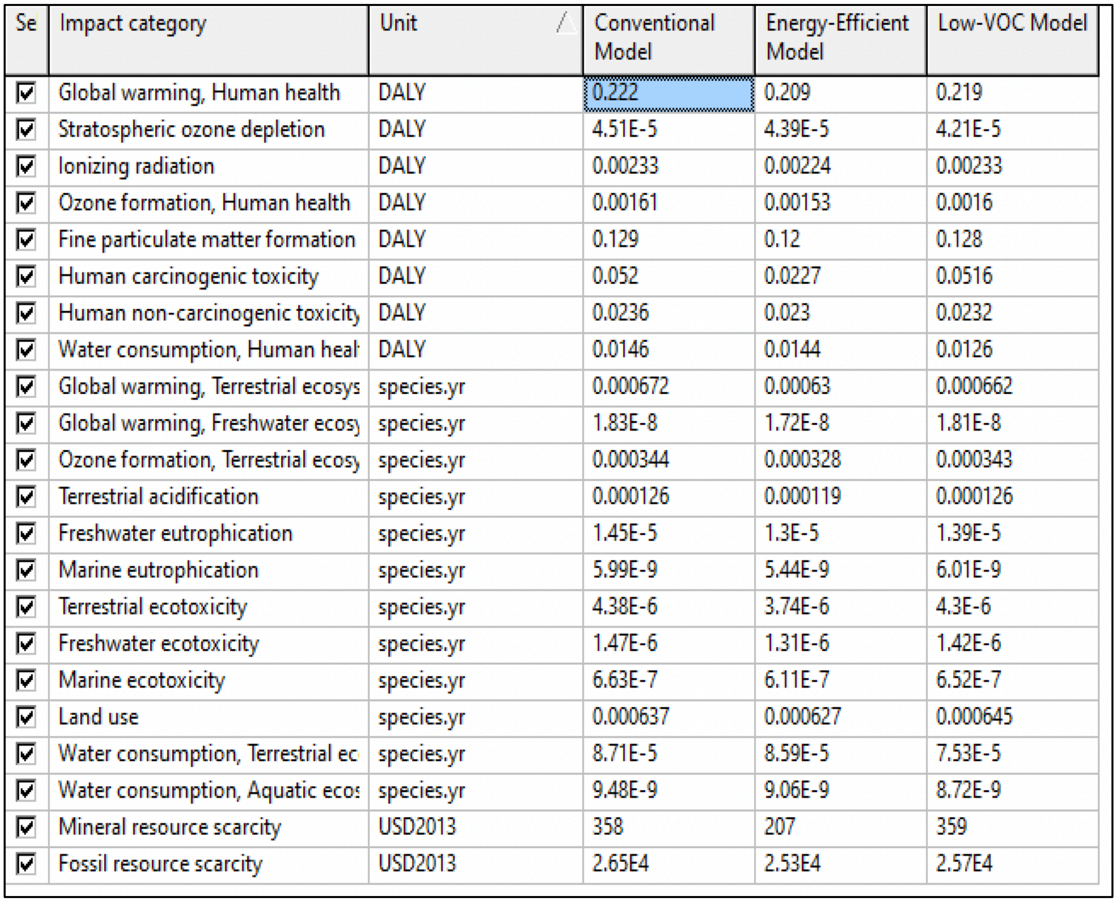
Se	Damage category	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model
☑	Human health		18.6	16.4	18.3
☑	Ecosystems		1.28	1.22	1.27
☑	Resources		0.957	0.911	0.931

Method: ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A / Normalization
Comparing 1 p 'Conventional Model', 1 p 'Energy-Efficient Model' and 1 p 'Low-VOC Model';

Figure 9. Normalized results of impacts for human health, ecosystems, and resources. *The y-axis represents the normalized units.*

Furthermore, when findings were sorted by impact category, “global warming, human health”, “fine particulate matter formation”, and “human carcinogenic toxicity” were the three categories that influenced the final DALY calculations the most (Table 5). Of these, the greatest difference (0.2922) between the Conventional Model and the Energy-Efficient Model was found in the “human carcinogenic toxicity” category, and the greatest difference (0.0031) between the Conventional Model and the Low-VOC Model was found in the “global warming, human health” category.

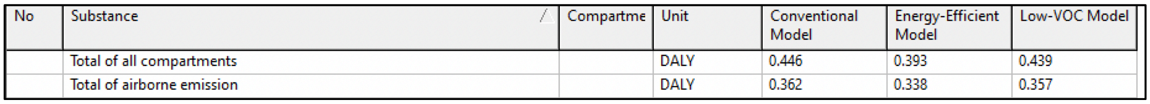
Table 5. Results for human health, ecosystems, and resources sorted by midpoint categories.



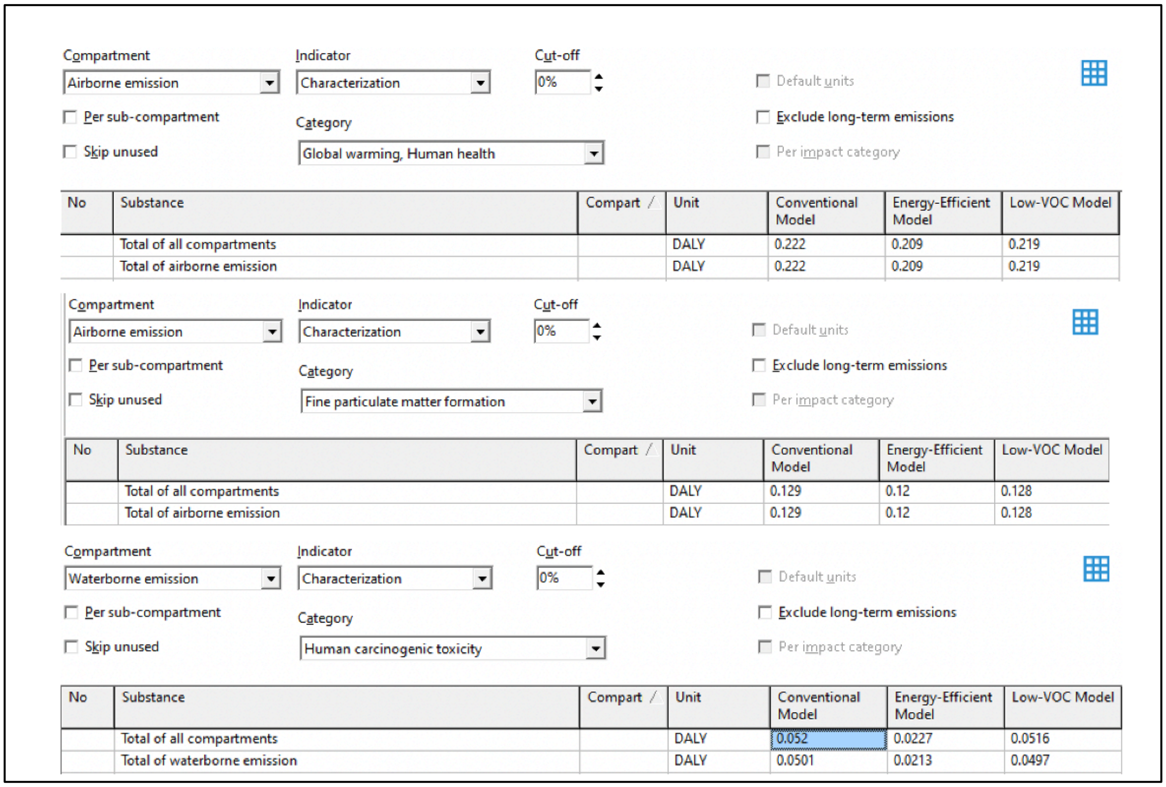
Se	Impact category	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model
☑	Global warming, Human health	DALY	0.222	0.209	0.219
☑	Stratospheric ozone depletion	DALY	4.51E-5	4.39E-5	4.21E-5
☑	Ionizing radiation	DALY	0.00233	0.00224	0.00233
☑	Ozone formation, Human health	DALY	0.00161	0.00153	0.0016
☑	Fine particulate matter formation	DALY	0.129	0.12	0.128
☑	Human carcinogenic toxicity	DALY	0.052	0.0227	0.0516
☑	Human non-carcinogenic toxicity	DALY	0.0236	0.023	0.0232
☑	Water consumption, Human heal	DALY	0.0146	0.0144	0.0126
☑	Global warming, Terrestrial ecosys	species.yr	0.000672	0.00063	0.000662
☑	Global warming, Freshwater ecos	species.yr	1.83E-8	1.72E-8	1.81E-8
☑	Ozone formation, Terrestrial ecos	species.yr	0.000344	0.000328	0.000343
☑	Terrestrial acidification	species.yr	0.000126	0.000119	0.000126
☑	Freshwater eutrophication	species.yr	1.45E-5	1.3E-5	1.39E-5
☑	Marine eutrophication	species.yr	5.99E-9	5.44E-9	6.01E-9
☑	Terrestrial ecotoxicity	species.yr	4.38E-6	3.74E-6	4.3E-6
☑	Freshwater ecotoxicity	species.yr	1.47E-6	1.31E-6	1.42E-6
☑	Marine ecotoxicity	species.yr	6.63E-7	6.11E-7	6.52E-7
☑	Land use	species.yr	0.000637	0.000627	0.000645
☑	Water consumption, Terrestrial ec	species.yr	8.71E-5	8.59E-5	7.53E-5
☑	Water consumption, Aquatic eco	species.yr	9.48E-9	9.06E-9	8.72E-9
☑	Mineral resource scarcity	USD2013	358	207	359
☑	Fossil resource scarcity	USD2013	2.65E4	2.53E4	2.57E4

Furthermore, of emission types (i.e., raw material, airborne emission, waterborne emission, final waste flow, emission to soil, non-material emission) between 80-86% of the final DALYs were impacted by airborne emission (Table 6). Of the three prevalent impact categories, both “global warming, human health” and “fine particulate matter formation” were almost 100% results of airborne emissions, while “human carcinogenic toxicity” was almost exclusively a result of waterborne emissions (Figure 10).

Table 6. Impact of airborne emissions on total DALYs.



No	Substance	Compartme	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model
	Total of all compartments		DALY	0.446	0.393	0.439
	Total of airborne emission		DALY	0.362	0.338	0.357



Compartment: Airborne emission
Indicator: Characterization
Cut-off: 0%
☐ Default units
☐ Per sub-compartment
Category: Global warming, Human health
☐ Exclude long-term emissions
☐ Skip unused
☐ Per impact category

No	Substance	Compart	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model
	Total of all compartments		DALY	0.222	0.209	0.219
	Total of airborne emission		DALY	0.222	0.209	0.219

Compartment: Airborne emission
Indicator: Characterization
Cut-off: 0%
☐ Default units
☐ Per sub-compartment
Category: Fine particulate matter formation
☐ Exclude long-term emissions
☐ Skip unused
☐ Per impact category

No	Substance	Compart	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model
	Total of all compartments		DALY	0.129	0.12	0.128
	Total of airborne emission		DALY	0.129	0.12	0.128

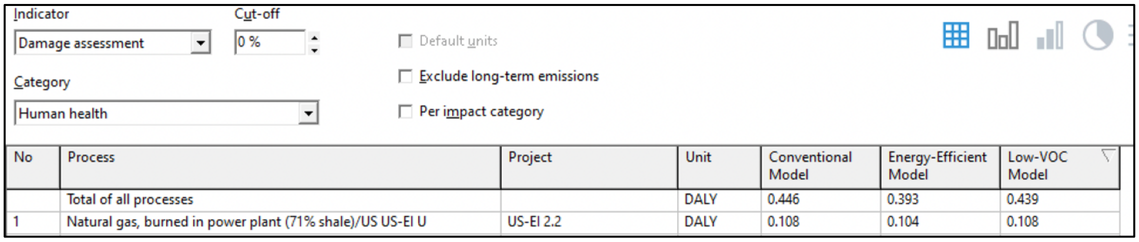
Compartment: Waterborne emission
Indicator: Characterization
Cut-off: 0%
☐ Default units
☐ Per sub-compartment
Category: Human carcinogenic toxicity
☐ Exclude long-term emissions
☐ Skip unused
☐ Per impact category

No	Substance	Compart	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model
	Total of all compartments		DALY	0.052	0.0227	0.0516
	Total of waterborne emission		DALY	0.0501	0.0213	0.0497

Figure 10. Emission factors according to three most prevalent midpoint categories.

When I observed process contribution on final DALYs, it was found that of the impact on human health, the greatest proportion (≈ 25%) was from Natural gas, burned in power plant (71% shale)/ US-EI U (Table 7).

Table 7. Process contribution toward human health results.



Indicator: Damage assessment

Cut-off: 0 %

Category: Human health

☐ Default units

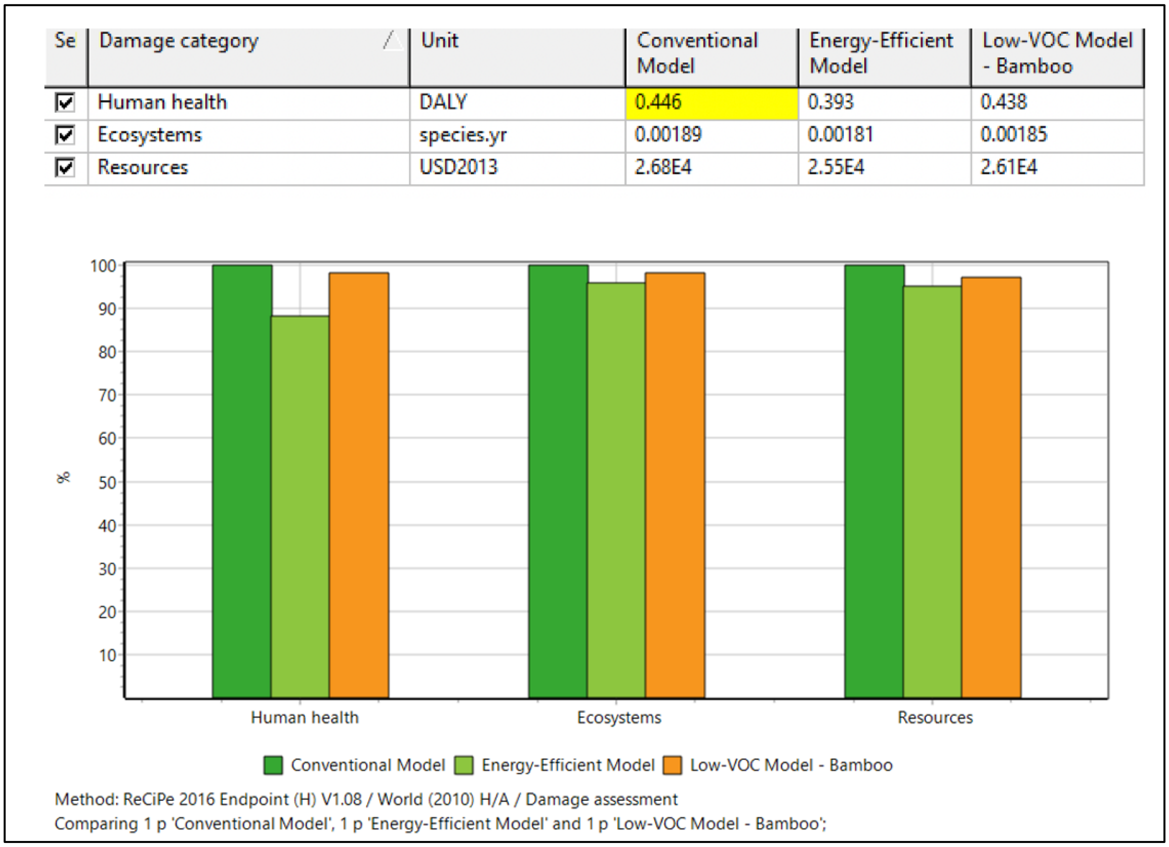
☐ Exclude long-term emissions

☐ Per impact category

No	Process	Project	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model
	Total of all processes		DALY	0.446	0.393	0.439
1	Natural gas, burned in power plant (71% shale)/US US-EI U	US-EI 2.2	DALY	0.108	0.104	0.108

Sensitivity Analyses

A sensitivity analysis was conducted to determine whether a change in low-VOC flooring (i.e., bamboo or hardwood), made a difference compared to the flooring in the Low-VOC Model. Both the bamboo flooring and the hardwood flooring led to ≈ 0.438 DALYs, a reduction of 0.001 DALYs. A sensitivity analysis was also run to determine the impact of a Combo Model that included both low-VOC materials and a heat pump. As would be expected, results for this model had the greatest reduction in DALYs from the Conventional Model, resulting in ≈ 0.386 DALYs. Findings are displayed below (Figure 11-13).

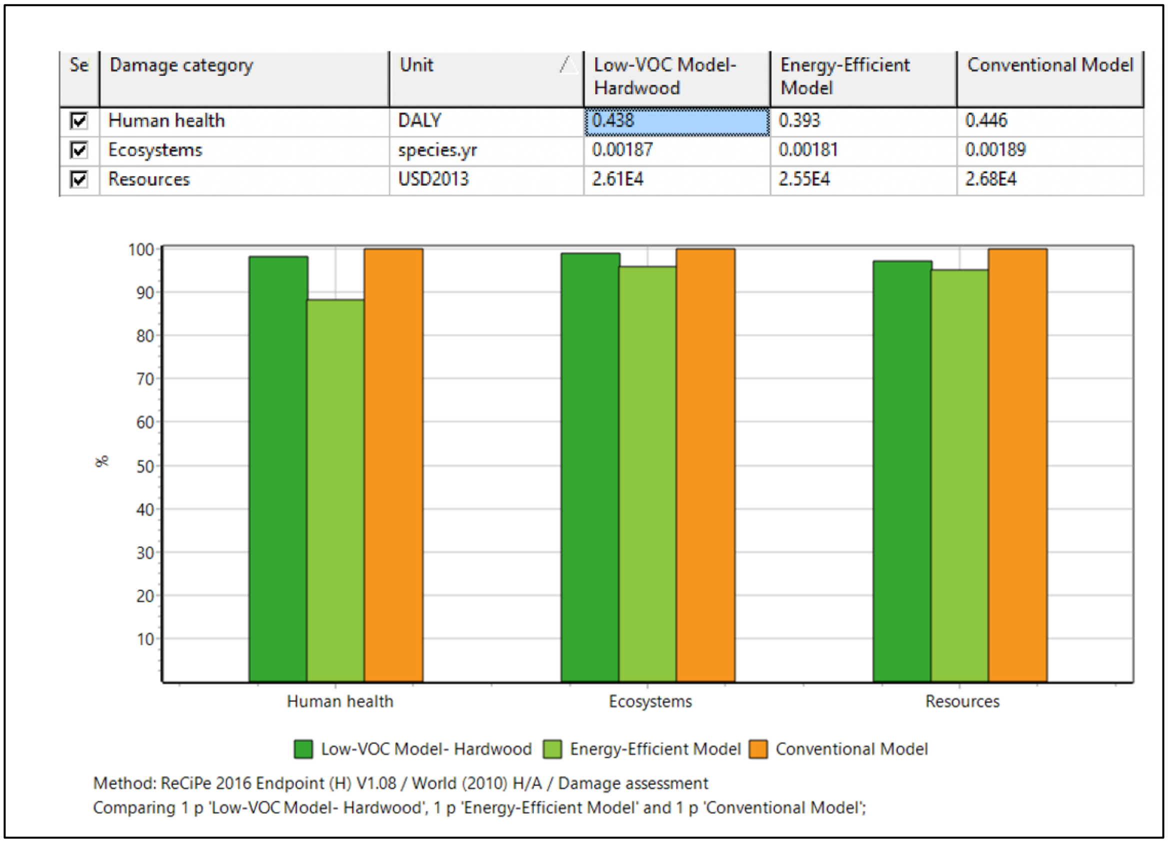


Se	Damage category	Unit	Conventional Model	Energy-Efficient Model	Low-VOC Model - Bamboo
☑	Human health	DALY	0.446	0.393	0.438
☑	Ecosystems	species.yr	0.00189	0.00181	0.00185
☑	Resources	USD2013	2.68E4	2.55E4	2.61E4

Method: ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A / Damage assessment
Comparing 1 p 'Conventional Model', 1 p 'Energy-Efficient Model' and 1 p 'Low-VOC Model - Bamboo';

Figure 11. Results for sensitivity analysis 1- bamboo flooring.

The y-axis is percentage of units (i.e., DALY, species.yr, USD2013) produced by the Conventional Model.

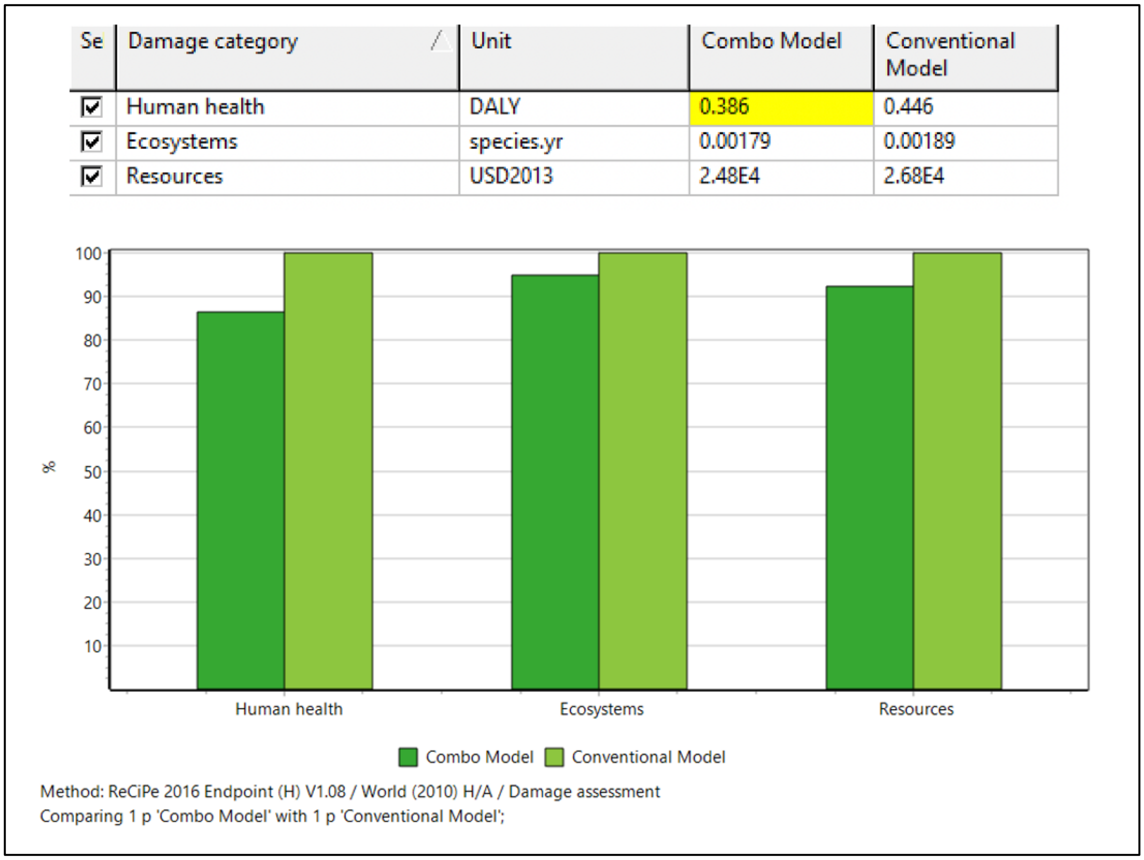


Se	Damage category	Unit	Low-VOC Model- Hardwood	Energy-Efficient Model	Conventional Model
☑	Human health	DALY	0.438	0.393	0.446
☑	Ecosystems	species.yr	0.00187	0.00181	0.00189
☑	Resources	USD2013	2.61E4	2.55E4	2.68E4

Method: ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A / Damage assessment
Comparing 1 p 'Low-VOC Model- Hardwood', 1 p 'Energy-Efficient Model' and 1 p 'Conventional Model';

Figure 12. Results for sensitivity analysis 2- hardwood flooring.

The y-axis is percentage of units (i.e., DALY, species.yr, USD2013) produced by the Conventional Model.



Se	Damage category	Unit	Combo Model	Conventional Model
☑	Human health	DALY	0.386	0.446
☑	Ecosystems	species.yr	0.00179	0.00189
☑	Resources	USD2013	2.48E4	2.68E4

Method: ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A / Damage assessment
Comparing 1 p 'Combo Model' with 1 p 'Conventional Model';

Figure 13. Results for Combo Model.

The y-axis is percentage of units (i.e., DALY, species.yr, USD2013) produced by the Conventional Model.

Scaled Results

Results for the Conventional Model, Energy-Efficient Model, and the Combo Model were scaled to represent the impact across a larger percentage of the NJ housing stock (Table 8). If 7% of the NJ housing stock (i.e., the percentage of stock comprised of 1970's single family detached homes) transitioned to a home with (1) an energy-efficient heat pump or (2) an energy efficient heat pump and low-VOC materials, there would be a reduction of 55 and 62 DALYs, respectively. These values grow exponentially as the percentage of homes that would transition increases (Figures 14-16).

Table 8. Resulting DALYs across three model types, scaled.

	Conventional Model	Energy Efficient (Heat Pump)	Low-VOC and Energy Efficient (Heat Pump)	Difference Between Conventional and Energy-Efficient Models	Difference Between Conventional and Low-VOC Models
7%	461	406	399	55	62
10%	659	581	570	78	89
15%	988	871	855	117	133
20%	1320	1160	1140	160	180
25%	1650	1450	1420	200	230
30%	1980	1740	1710	240	270
35%	2310	2030	1990	280	320
40%	2630	2320	2280	310	350

Percentage indicates percentage of the NJ housing stock.

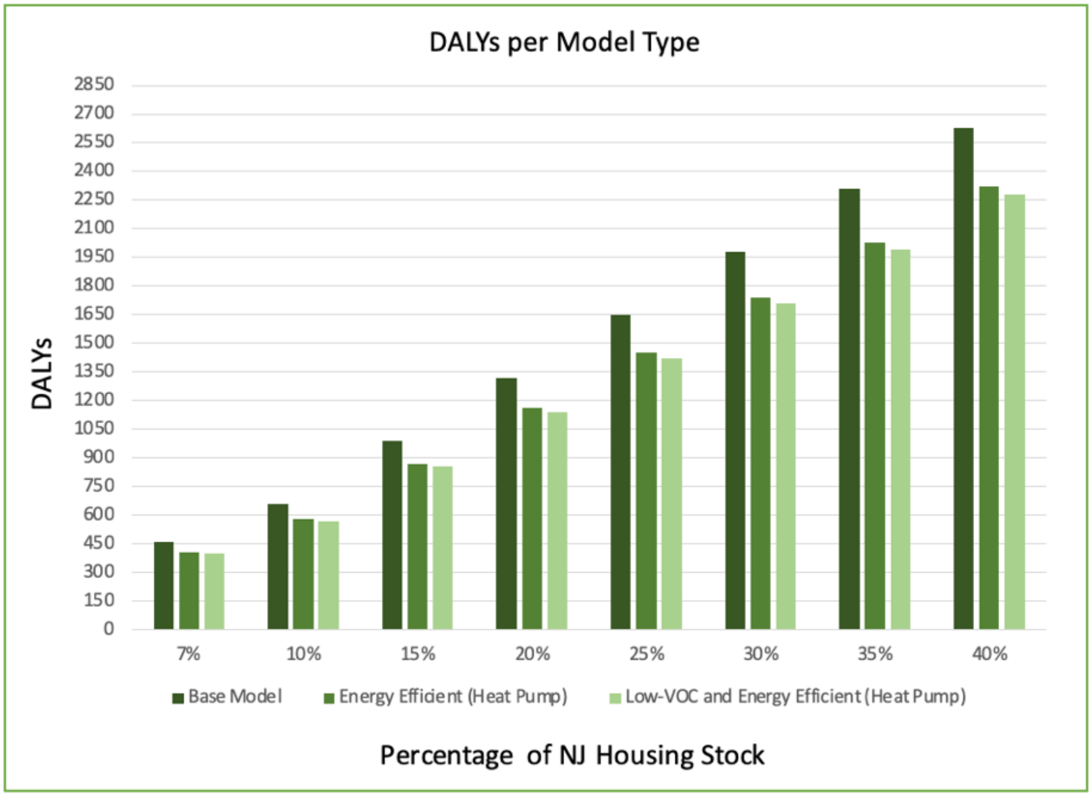


Figure 14. DALYs across three model types, scaled.

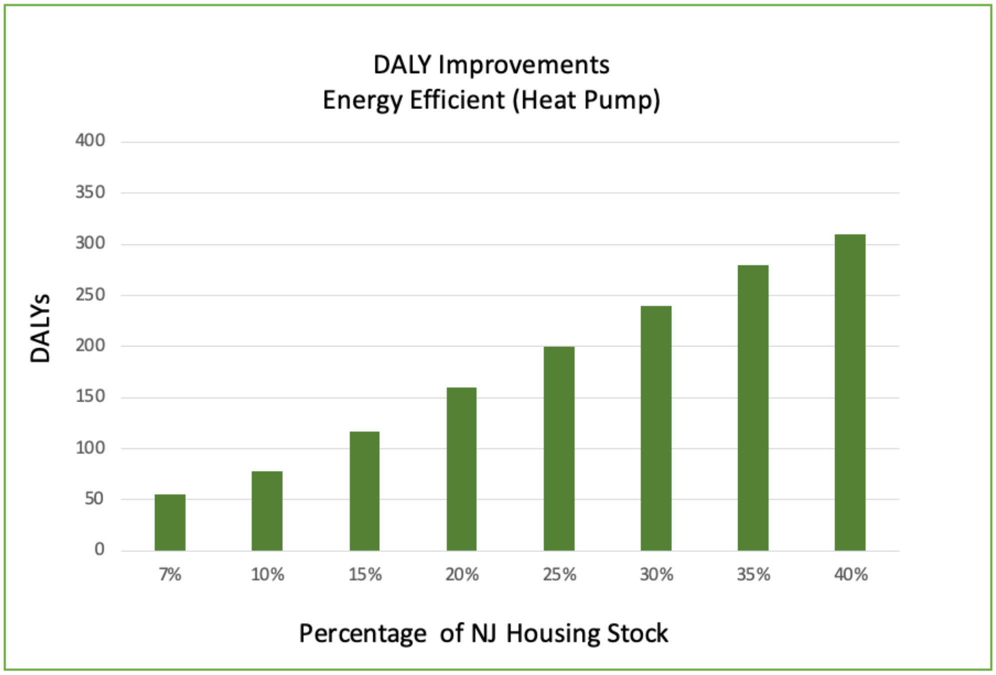


Figure 15. DALYs reduction from Conventional Model to Energy-Efficient Model, scaled.

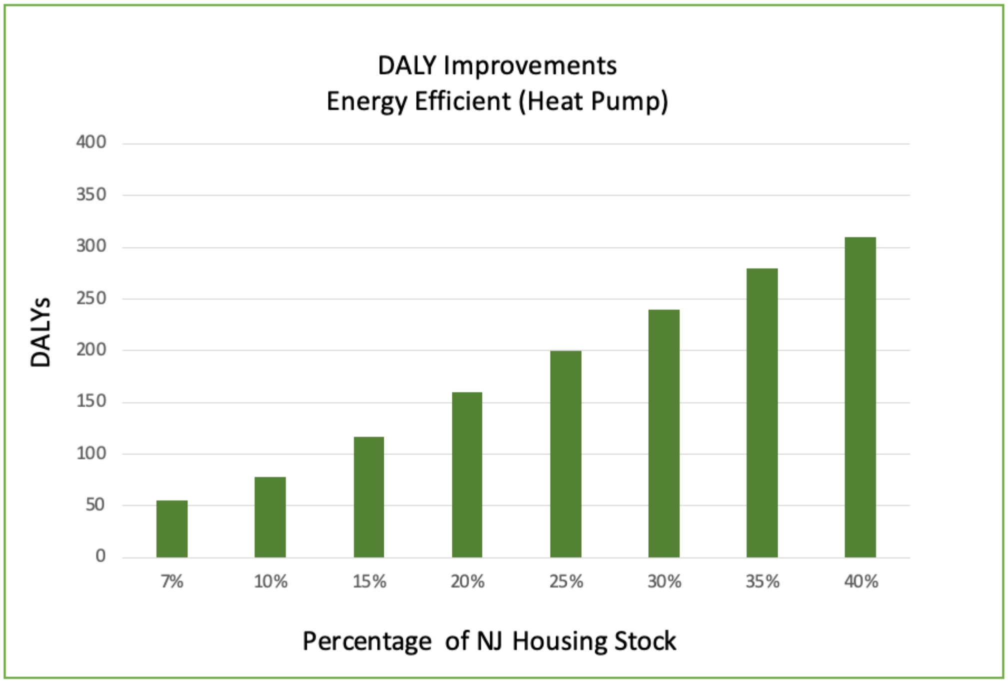
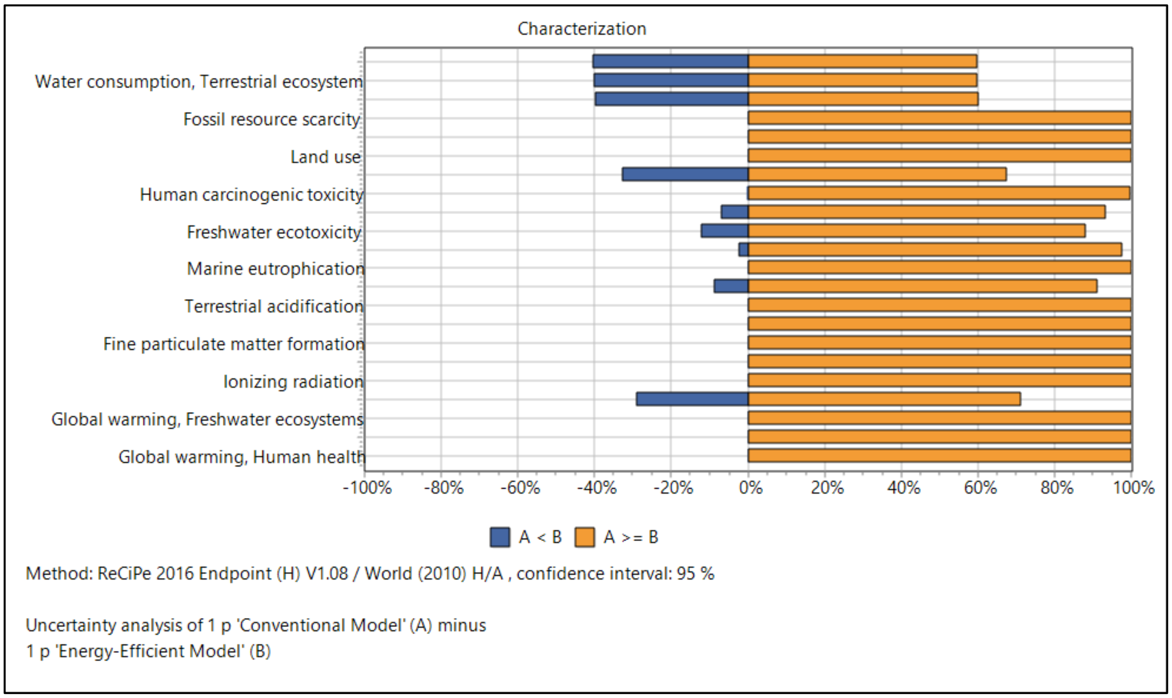


Figure 16. DALYs reduction from Conventional Model to Combo Model, scaled.

Monte Carlo Uncertainty Analysis Results

Across the midpoint categories, the Energy-Efficient Model outperformed the Conventional Model (Figure 17). The orange bars represent the number of times the Energy-Efficient Model had a lower load than the Conventional Model.

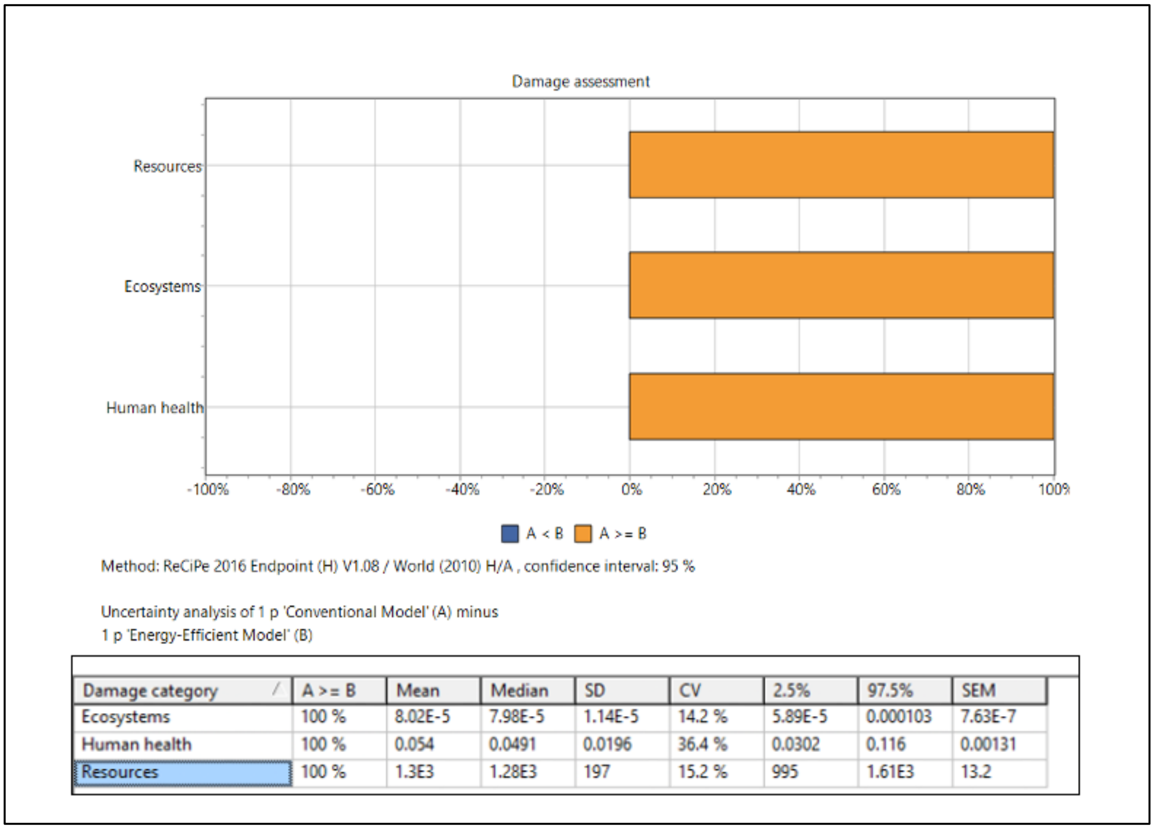


Method: ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A , confidence interval: 95 %

Uncertainty analysis of 1 p 'Conventional Model' (A) minus
1 p 'Energy-Efficient Model' (B)

Figure 17. Monte Carlo uncertainty analysis results- impact characterization.

Furthermore, when ‘Damage Assessment’ was evaluated, the Energy-Efficient Model outperformed the Conventional Model in 100% of the cases regarding Human Health, meaning that it was almost certain that for Human Health, a change to an energy-efficient heat pump would be beneficial (Figure 18).



Method: ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A , confidence interval: 95 %

Uncertainty analysis of 1 p 'Conventional Model' (A) minus
1 p 'Energy-Efficient Model' (B)

Damage category	A >= B	Mean	Median	SD	CV	2.5%	97.5%	SEM
Ecosystems	100 %	8.02E-5	7.98E-5	1.14E-5	14.2 %	5.89E-5	0.000103	7.63E-7
Human health	100 %	0.054	0.0491	0.0196	36.4 %	0.0302	0.116	0.00131
Resources	100 %	1.3E3	1.28E3	197	15.2 %	995	1.61E3	13.2

Figure 18. Monte Carlo uncertainty analysis results- damage assessment.

Chapter IV

Discussion

Findings across the different models and scenarios suggested that there was a definite relationship between sustainable buildings and their impact on health. Compared to the Conventional Model, both the Low-VOC Model and the Energy-Efficient Model resulted in improved DALYs. While results did not specify which of the three green building programs (i.e., LEED, WELL, or Passive House) had the greatest impact on health, they do help understand how sustainable building features within these programs influence health.

LEED and Passive House programs support the Energy-Efficient Model, both presenting a heat pump as an alternative to traditional fossil-fueled heating. Although energy efficiency does not prioritize human health in its design, the results suggest that its impacts on health should be equally valued, as normalization values found that human health impacts were roughly 14x greater than ecosystems impacts.

These effects on well-being may be a result of lessened demand on energy production and subsequent reduced emissions from fossil fuels. The greatest differences were observed between the Convention Model and Energy-Efficient Model, regarding the midpoint characteristics “human carcinogenic toxicity”, “global warming, human health”, and “fine particulate matter formation”. With further investigation, I observed that of the DALYs recorded for each model, approximately between 80-86% were a direct result of airborne emissions, which supports the previous knowledge that fossil fueled heating sources emit substances, such as particulate matter and NOx, that negatively impact well-being and are triggers for asthma, heart conditions, and other chronic illnesses. This is further supported by the findings that airborne emissions were 100% of the emissions calculated in total emissions for the two prevalent impact categories “global warming, Human health” and “fine particulate matter formation.” Moreover, while this thesis only tested the impact of an upgrade from a traditional fossil-fueled furnace HVAC system to an air-source heat pump, it can be plausibly inferred that a similar change from a fossil-fueled water heater to a heat pump water heater would result in an even greater improvement (reduction) in DALYs. Therefore, this thesis is timely, as results pointed to an additional benefit to the intended decarbonization goals of national movements to drive heat pump adoption, such as the 2022 Inflation Reduction Act and the Memorandum of Understanding (Inflation reduction act, 2022; MacMunn, 2024).

While results did not support the expected hypothesis that the Low-VOC Model would result in the greatest reduction in DALYs compared to the Conventional Model, it does not mean that low-VOC materials do not have an equally relevant impact on health. The WELL program prioritizes eco-friendly and nontoxic materials within their homes for a reason. Nevertheless, LCA methods do not accurately evaluate the impact of different materials on health, as they do not consider the effects of material toxicity on occupants over its lifetime. It is well known that certain materials (e.g., paints, floor coatings, couches) release chemicals through off-gassing, photo-degradation, and abrasion for a period of time after installation. The intensity of these emissions tapers over time, with the worse of their impacts immediately after installation (Wu & Apul, 2015). Low and Zero-VOC materials drastically reduce risk of toxic chemical emissions, cutting the intensity and length of emissions compared to the alternative.

The LCA model evaluated the production of the structural built materials and the energy demand of the homes during their use phase. As a result, health impacts were considered in terms of production and use emissions and were applied to the general public, as well as occupants. For example, the greatest improvement in DALYs was observed when the Conventional Model was upgraded to the Energy-Efficient Model, but emissions did not account for material toxicity impacts on the occupant itself. If the LCA were to also evaluate the impact of the built materials' toxicity on occupants, there is a possibility that a home with low-VOC materials would have greater impact on DALYs than previously observed, possibly equal to that of the Energy-Efficient Model. This is not to disregard the health impacts of the Energy-Efficient Model stated above, rather it is just to say that other aspects of these homes might boost the effects on health (i.e., ventilation and air quality, low-emitting materials), as they are not considered within an LCA. Results from the Combo Model tested in the sensitivity analysis support this notion, as it indicated the greatest reduction of DALYs across all tests.

While this analysis was unable to determine whether impacts would apply mostly to occupants or the general public, results demonstrated that the process with the greatest contribution toward DALY output for the Energy- Efficient Model (≈ 26%) was natural gas, burned in power plants (71% shale)/ US-EI U. Therefore, it can be inferred that production had a prevalent impact on final DALYs and subsequently would impact the general public to a greater extent. This is not to say that occupants would not feel the impacts of fossil-fueled heating and emitting materials. Rather, the fact that the impact of natural gas increased from 24% for the Conventional Model to 26% for the Energy-Efficient Model, suggests that because of the lack of a fossil-fueled heating system, more emissions came from the production of the heat pump than from its use. This is similarly observed with the Low-VOC Model, as approximately 25% of total DALYs were a result of Natural gas, burned in power plant (71% shale)/ US-EI U. Therefore, while occupants would still be affected, the general public would feel impacts more greatly simply because of the increased contribution that production had in the total life cycle emissions. When observing impact results of traditional materials versus low-VOC materials in the Low-VOC Model, it is important to additionally consider that because of the LCA's limitations, results may have underestimated the impact of certain emissions on occupants.

The limitations of the LCA model could also point to the reason that bamboo and hardwood flooring options in the sensitivity analysis varied by a minimal amount (0.001). As the emissions and subsequent health impacts from the production phase were similar across the three flooring types, findings suggested that they had a similar effect on DALYs. Yet, if their material toxicity and post-production emissions were to be included in the analysis, it is plausible that results would be different.

There are currently several approaches used to contemplate clean energy transitions that also estimate health impacts. For example, Grid Expansion Planning is a linear least cost optimization model that when linked with COBRA can estimate health impacts on a county- scale (Rutgers University, work in progress, 2024). Integrated Energy Planning, which is also based on least-cost optimization modeling and includes demand side changes and supply side ones, incorporates a building stock model that allows for various rates of transition and associated investment costs simulations as well as formula-based health impact calculations (New Jersey 2019 IEP Technical Appendix, 2019).

This thesis supplements the already growing arsenal of optimal building decision support tools through LCA methodology that, in this case, proposes practical retrofits for homeowners. Consequently, it offers a paired human-technological micro foundation for better understanding the possible mutual relationship between clean energy changes to housing and beneficial health strategies, and how beneficial health strategies may be employed independently.

Nevertheless, much like other methods of research, LCA capabilities are limited. LCA inputs require particular data that revolve around the production of an item and its impact on the environment (Rey-Álvarez et al., 2022) These include raw material extraction, transportation, construction, use, demolition, etc. Although an LCA of a building, or even a green building, is not a new concept — the home becomes the "item" and each stage is analyzed in terms of its impacts on the environment — its use has been limited primarily to understanding the energy demands or carbon impact of a building, with impact on health taking the back seat (Rey-Álvarez et al., 2022).

As a result, the incorporation of material toxicity into LCAs is immature. While an LCA can evaluate the toxicity of a product, its results vary greatly from one software to another due to a "lack of characterization of substances and their standardization" in databases and findings that rarely reflect the impact of a substance throughout its entire life cycle (Rey-Álvarez et al., 2022). This lack of standardization, characterization, and understanding of product's long-term effects is an obstacle when integrating material toxicity into LCAs, as it makes it difficult to obtain accurate results that do not underestimate the impact of a material’s emissions (Rey-Álvarez et al., 2022).

The lack of standardization is also found in the healthy material industry, as well. While EPDs are found across the industry, HPDs, which aim to provide a full disclosure of potential hazards in green building materials, are a recent 2012 addition (HPD Collaborative, 2022). HPDs are self-disclosed from manufacturers and are not required, although many green building standards have begun to require them for all products included in the build (Vittori, 2023). Third party certifications (e.g., Cradle to Cradle) and toxic material lists (e.g., Living Building Challenge Red List) are only just beginning to set a standard for transparency in the industry (HPD Collaborative, 2022; International Living Future Institute, 2023) Policy and regulations are slow to change, as both the public and manufacturers benefit from maintaining the status quo (Andrews, 2023; Chiapella et al., 2019). Nevertheless, with time, an integrated and standardized chemical inventory that presents data accurately and efficiently will provide a better opportunity for future awareness and research.

Both health and sustainability within the built industry are relevantly new and emerging. For this reason, research on their relationship varies greatly in topic (e.g., mental health to physiological improvements), as well as methods and forms of measurement (e.g., occupants surveys, hospital records, IAQ measurements) (Allen et al., 2015; Liu et al., 2023). While findings help uncover the reality of their relationship, it is difficult to draw concrete conclusions when there is such variance. Furthermore, many studies are limited in their sample sizes, objective measures of health, and specific details about green building credits (Allen et al., 2015; Liu et al., 2023). Therefore, deciding which methods and metrics provide the most accurate depiction of well-being in a building is an important task of future research that will be essential to the industry.

As mentioned previously, an LCA is unable to model human behavior. As both determinants are valued greatly in the program guides and might have a greater impact on well-being, it is equally important to continue research on their relationship with health (Lin et al., 2017). Much the same, although LCAs provide outputs related to health (e.g., DALYS, CTUcancer, CTUnoncaner, CTUecotoxicity, human health criteria pollutants), what they measure, and their indication of health, differs greatly from one another.

Therefore, to best understand the impacts of buildings on health, I suggest future research should focus on constructing a standardized inventory for chemical materials and their toxicity to efficiently represent their impacts on the environment and health. Subsequently, I suggest creating a modality that incorporates this inventory and IAQ measurements into an LCA methodology to offer a comprehensive, but objective means to evaluate health.

Conclusions

This research aimed to identify the health benefits of green buildings to better evaluate the current sustainable building programs and provide new insights on the relationship between well-being and the built environment. Through a comparative LCA between a Convention Model (i.e., 1970’s vintage home), a Low-VOC Model, and an Energy-Efficient Model, findings supported the hypothesis that sustainable building elements incorporated into the retrofit of a conventionally built home resulted in a greater improvement (decrease) in DALYs. As the Energy-Efficient Model resulted in the greatest reduction of DALYs from the Conventional Model, it can be inferred that programs that prioritize heat pumps and movements to decarbonize heating systems will simultaneously benefit the environment and the well-being of potential occupants and the general population. As this research aimed to study plausible upgrades for homeowners, it may help current homeowners better prioritize the adoption of energy-efficient heat pumps and low-VOC materials to improve their health.

Throughout this thesis journey, I have found that uncovering a full understanding of the relationship between health and buildings is much easier said than done. With varying methods and forms of measurement, research into health and buildings, specifically the impact of sustainable building programs, is still rather immature. This is observed in the limited capabilities of an LCA to represent the impact of a building on human health, as software is tailored to reflect the environmental impact of a product. Much the same, emerging awareness of material toxicity in the industry must continue to develop before accurate depictions can be observed. Therefore, while results of this thesis offer new insights to the field, with improved research modalities surrounding health and the built environment, it is expected that future findings will be adjusted as data becomes more reliable and extensive.

Appendix

Data Inputs for SimaPro

Table 9. Complete list of data inputs for SimaPro for all models.

Conventional Model	
Walls	
1/2" Moisture Resistant Gypsum Board	Gypsum plaster board, at plant/US* US-EI U
Polyethylene House Wrap	Polyethylene, HDPE, granulate, at plant/US- US-EI U
Double Glazed No Coating Air Windows	Glazing, double (2-IV), U<1.1 W/m2K, at plant/US- US-EI U
Expanded Polystyrene Sheets Insulation	Polystyrene foam slab, at plant/US- US-EI U
Glass Fibre	Glass fibre, at plant/US- US-EI U
Laminated Veneer Lumber	Laminated veneer lumber, at plant, US SE/kg NREL/US U
Softwood Lumber, Kiln Dried	Sawn timber, softwood, planed, kiln dried, at plant/US- US-EI U
Softwood Plywood	Plywood, indoor use, at plant/US- US-EI U
Wood Window Frame	Window frame, wood, U=1.5 W/m2K, at plant/US- US-EI U
Water Based Acrylic Paint	Acrylic varnish, 87.5% in H2O, at plant/US- US-EI U
Ceramic Tile	Ceramic tile {CH}| ceramic tile production | Cut-off, U with US electricity

Conventional Model Walls	
Mortar	Cement mortar {CH}| cement mortar production | Cut-off, U with US electricity
Flooring	
Galvanized Steel Sheet	Galvanized steel sheet, at plant NREL/RNA U
Softwood Lumber	Galvanized steel sheet, at plant NREL/RNA U
Softwood Plywood	Plywood, indoor use, at plant/US- US-EI U
Ceramic Tile	Ceramic tile {CH}| ceramic tile production | Cut-off, U with US electricity
Cement Backer Board	Gypsum fibre board, at plant/US* US-EI U
Mortar	Cement mortar {CH}| cement mortar production | Cut-off, U with US electricity
Carpet	- Fibre, polyester {IN}| polyester fibre production, finished | Cut-off, U with US electricity -Textile, nonwoven polypropylene {IN}| textile production, nonwoven polypropylene, spunbond | Cut-off, U with US electricity
Flooring	Glued laminated timber, indoor use, at plant/US- US-EI U
Foundation	
Concrete Benchmark 3000 Psi	Poor concrete, at plant/US* US-EI U
Welded Wire Mesh/Ladder Wire	Reinforcing steel, at plant/US- US-EI U
Roofing	
Felt	Bitumen sealing, polymer EP4 flame retardant, at plant/US- US-EI U

Conventional Model	
Roofing	
Shingles	Mastic asphalt {CH}| mastic asphalt production | Cut-off, U with US electricity
Galvanized Steel Sheet	Galvanized steel sheet, at plant NREL/RNA U
Softwood Lumber	Sawn timber, softwood, planed, kiln dried, at plant/US- US-EI U
Softwood Plywood	Plywood, outdoor use, at plant/US- US-EI U
Doors	
Inside Doors	Door, inner, wood, at plant/US- US-EI U
Outside Doors	Door, outer, wood-aluminium, at plant/US- US-EI U
HVAC System	
Ventilation	Ventilation system, central, 1 x 720 m3/h, steel ducts, with GHE/US*/I US-EI U modified for 157m2 (1690 ft2). Excludes transportation from production to site.
Heating And Cooling	- Industrial furnace, natural gas/US-/I US-EI U - Refrigerant R134a, at plant/US- US-EI U - Blower and heat exchange unit, decentralized, 180-250 m3/h {RER}| blower and heat exchange unit production, decentralized, 180-250 m3/h | Cut-off, U with US electricity - Tube insulation, elastomere, at plant/US** US-EI U
Low-VOC Model	
Walls	
1/2" Moisture Resistant Gypsum Board	Gypsum plaster board, at plant/US* US-EI U

Low-VOC Model

Walls	
Polyethylene House Wrap	Polyethylene, HDPE, granulate, at plant/US- US-EI U
Double Glazed No Coating Air Windows	Glazing, double (2-IV), U<1.1 W/m2K, at plant/US- US-EI U
Expanded Polystyrene Sheets Insulation	Polystyrene foam slab, at plant/US- US-EI U
Glass Fibre	Glass fibre, at plant/US- US-EI U
Laminated Veneer Lumber	Laminated veneer lumber, at plant, US SE/kg NREL/US U
Softwood Lumber, Kiln Dried	Sawn timber, softwood, planed, kiln dried, at plant/US- US-EI U
Softwood Plywood	Plywood, indoor use, at plant/US- US-EI U
Wood Window Frame	Window frame, wood, U=1.5 W/m2K, at plant/US- US-EI U
No VOC Water-Based Paint	ECOS paint: modified “Acrylic varnish, 87.5% in H2O, at plant/US- US-EI U” to include: Water, ultrapure, at plant/GLO US-EI U; Titanium dioxide {RoW}| titanium dioxide production, sulfate process | Cut-off, U; Methyl methacrylate {RoW}| methyl methacrylate production | Cut-off, U; Limestone, crushed, washed/US* US-EI U; Calcium carbonate, precipitated {RoW}| calcium carbonate production, precipitated | Cut-off, U; Potassium chloride (NPK 0-0-60), at plant {RER} Economic, U; Kaolin, at plant/US- US-EI U; Silicone product, at plant/US- US-EI U; Acrylic binder, 34% in H2O, at plant/US- US-EI U; Vinyl acetate, at plant/US- US-EI U; Sodium hydroxide, production mix, at plant/RNA; Paraffin, at plant/US- US-EI U; Hydrogen peroxide, 50% in H2O, at plant/US- US-EI U; Sodium chloride, at plant/RNA.

Low-VOC Model	
Walls	
Ceramic Backer Board	Gypsum fibre board, at plant/US* US-EI U
Mortar	Cement mortar {CH}| cement mortar production | Cut-off, U with US electricity
Flooring	
Galvanized Steel Sheet	Galvanized steel sheet, at plant NREL/RNA U
Softwood Lumber	Galvanized steel sheet, at plant NREL/RNA U
Softwood Plywood	Plywood, indoor use, at plant/US- US-EI U
Ceramic Tile	Ceramic tile {RoW}| ceramic tile production | Cut-off, U
Cement Backer Board	Gypsum fibreboard {RoW}| gypsum fibreboard production | Cut-off, U
Mortar	Cement mortar {RoW}| cement mortar production | Cut-off, U
Flooring	Glued laminated timber, indoor use, at plant/US- US-EI U Modified to replace Urea formaldehyde resin, at plant/US* US-EI U with Polyester resin, unsaturated {US}| soy-based resin production | Cut-off, U.
Foundation	
Concrete Benchmark 3000 Psi	Poor concrete, at plant/US* US-EI U
Welded Wire Mesh/Ladder Wire	Reinforcing steel, at plant/US- US-EI U
Roofing	
Felt	Bitumen sealing, polymer EP4 flame retardant, at plant/US- US-EI U
Shingles	Mastic asphalt {CH}| mastic asphalt production | Cut-off, U with US electricity
Galvanized Steel Sheet	Galvanized steel sheet, at plant NREL/RNA U

Low-VOC Model	
Roofing	
Softwood Lumber	Sawn timber, softwood, planed, kiln dried, at plant/US- US-EI U
Softwood Plywood	Plywood, outdoor use, at plant/US- US-EI U
Doors	
Inside Doors	Door, inner, wood, at plant/US- US-EI U
Outside Doors	Door, outer, wood-aluminum, at plant/US- US-EI U
HVAC System	
Ventilation	Ventilation system, central, 1 x 720 m3/h, steel ducts, with GHE/US*/I US-EI U modified for 157m2 (1690 ft2). Excludes transportation from production to site.
Heating And Cooling	-Industrial furnace, natural gas/US-/I US-EI U -Refrigerant R134a, at plant/US- US-EI U -Blower and heat exchange unit, decentralized, 180-250 m3/h {RER}| blower and heat exchange unit production, decentralized, 180-250 m3/h | Cut-off, U with US electricity -Tube insulation, elastomere, at plant/US** US-EI U
Energy-Efficient Model	
Walls	
1/2" Moisture Resistant Gypsum Board	Gypsum plaster board, at plant/US* US-EI U
Polyethylene House Wrap	Polyethylene, HDPE, granulate, at plant/US- US-EI U
Double Glazed No Coating Air Windows	Glazing, double (2-IV), U<1.1 W/m2K, at plant/US- US-EI U

Energy-Efficient Model **Walls**	
Expanded Polystyrene Sheets Insulation	Polystyrene foam slab, at plant/US- US-EI U
Glass Fibre	Glass fibre, at plant/US- US-EI U
Laminated Veneer Lumber	Laminated veneer lumber, at plant, US SE/kg NREL/US U
Softwood Lumber, Kiln Dried	Sawn timber, softwood, planed, kiln dried, at plant/US- US-EI U
Softwood Plywood	Plywood, indoor use, at plant/US- US-EI U
Wood Window Frame	Window frame, wood, U=1.5 W/m2K, at plant/US- US-EI U
Water-Based Acrylic Paint	Acrylic varnish, 87.5% in H2O, at plant/US- US-EI U
Ceramic Tile	Ceramic tile {CH}| ceramic tile production | Cut-off, U with US electricity
Ceramic Backer Board	Gypsum fibre board, at plant/US* US-EI U
Mortar	Cement mortar {CH}| cement mortar production | Cut-off, U with US electricity
Flooring	
Galvanized Steel Sheet	Galvanized steel sheet, at plant NREL/RNA U
Softwood Lumber	Galvanized steel sheet, at plant NREL/RNA U
Softwood Plywood	Plywood, indoor use, at plant/US- US-EI U
Ceramic Tile	Ceramic tile {RoW}| ceramic tile production | Cut-off, U

Energy-Efficient Model	
Flooring	
Mortar	Cement mortar {RoW}| cement mortar production | Cut-off, U
Carpet	- Fibre, polyester {RoW}| polyester fibre production, finished | Cut-off, U - Textile, nonwoven polypropylene {RoW}| textile production, nonwoven polypropylene, spunbond | Cut-off, U
Flooring	- Glued laminated timber, indoor use, at plant/US- US-EI U
Foundation	
Concrete Benchmark 3000 Psi	Poor concrete, at plant/US* US-EI U
Welded Wire Mesh/Ladder Wire	Reinforcing steel, at plant/US- US-EI U
Roofing	
Felt	Bitumen sealing, polymer EP4 flame retardant, at plant/US- US-EI U
Shingles	Mastic asphalt {CH}| mastic asphalt production | Cut-off, U with US electricity
Galvanized Steel Sheet	Galvanized steel sheet, at plant NREL/RNA U
Softwood Lumber	Sawn timber, softwood, planed, kiln dried, at plant/US- US-EI U
Softwood Plywood	Plywood, outdoor use, at plant/US- US-EI U
Doors	
Inside Doors	Door, inner, wood, at plant/US- US-EI U
Outside Doors	Door, outer, wood-aluminium, at plant/US- US-EI U

Energy-Efficient Model	
HVAC System	
Ventilation	Ventilation system, central, 1 x 720 m3/h, steel ducts, with GHE/US*/I US-EI U modified for 157m2 (1690 ft2). Excludes transportation from production to site.
Heating And Cooling	-Heat pump, brine-water, 10kW/US*/I US-EI U, edited to exclude transport. - Borehole heat exchanger 150 m/US*/I US-EI U
Sensitivity Analysis: Low-VOC Bamboo Flooring	
Flooring	Glued laminated bamboo, indoor use, at plant/US- US-EI U Modified to replace Urea formaldehyde resin, at plant/US* US-EI U with Polyester resin, unsaturated {US}| soy-based resin production | Cut-off, U.
Sensitivity Analysis: Low-VOC Hardwood Flooring	
Flooring	Glued solid timber {RER}| glued solid timber production | Cut-off, U, with US electricity.

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