Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

Tazrin Ahmed

Effect of energy standard on energy and materials use intensity associated with GHG emission from building envelope in U.S. office buildings

Master's thesis in Circular Economy
Supervisor: Edgar Hertwich
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Abstract

Studies have shown that the existing building stocks consume about 40% of the energy and resources around the world. They are also responsible for one-third of the total global greenhouse gas (GHG) emissions. Commercial buildings, among others, consume a relatively higher amount of energy that eventually adds up to a significant amount of life cycle greenhouse gas (GHG) emission that translates into high global warming potential (GWP). The rapid growth of commercial building stock observed through the past few decades in the U.S. impose great demand on the energy sector, which calls for urgent measures for improvement. The U.S. Department of Energy (DOE) supported several programs to improve energy use in buildings through standards and laws which provide benchmark values for different types of buildings. Energy standards were developed by the American Society for Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE). It proposes benchmark values for energy use per floor area and observes the energy performance of existing and new buildings in different states.

While energy standard-specific improvements offer potential savings for energy consumption and GHG emission, they often fail to address the role of materials associated with achieving these benchmarked values. Therefore, in this thesis, the impacts of materials used in the building envelop envelope (i.e., exterior wall and window) are thoroughly studied in relation to the most advanced ASHRAE 90.1-2019 energy standards. For this purpose, two types of office buildings, large and medium, with an area of are considered. Relation between energy and material use is studied by altering location, geometric composition, material, and construction type per components used in the building envelope.

Theoretic materials used in Pacific Northwest National Laboratory (PNNL) developed models are used as a reference to compare alternative materials. The two alternative models are created using cross-laminated timber and steel framed concrete with cavity insulation as exterior wall material. Both types of office buildings are modeled using two types of curtain wall materials. The model with steel-framed concrete wall uses a curtain wall with Low-E double-paned glass and aluminum mullions. And the cross-laminated timber wall model uses a curtain wall with reflexive double-paned glass and wooden mullion. The locations are selected based on the commitment to adapt energy standards in growing U.S. cities. Four cities, namely New York City, Buffalo, Seattle, and Honolulu, are selected for their distinct climatic characteristics.

Energy models for these buildings are primarily built in EnergyPlus version 9.2.0 energy simulation software. The environmental performance is exclusively assessed in terms of global warming potentials (GWP), expressed in kgCO_2e, for energy (kWh) and material (kg) use per 1 m^2 of gross floor area in a year. The environmental performance is conducted according to the life cycle assessment method for buildings. The results from energy simulation and GWP are also compared using different versions of energy standards in different climatic regions

Results show that, with changing wall and window ratio in the exterior wall, materials demand per square meter floor area either doubled or halved. Increased window area halved material demand for the wall material, and decreased window area doubled this demand. Among the two alternatives, the cross-laminated timber wall system required less amount of material compared to the steel-framed concrete with a cavity insulation system.

In terms of annual energy use intensity (EUI), large and medium office results range between 156 to 192 kWh/m^2, and 80 to 116 kWh/m^2, respectively. The material use intensity (MUI) for the large office envelop system in the large office building ranges between 23 to 105 kg/m^2. The lowest and highest value corresponds with WWR of 90% and 20% respectively. For medium office envelop, MUI ranges between 21 to 150 kg/m^2. The lowest and highest values come from envelops with WWR of 70% and 15%, respectively.

The total GWP from energy use and materials fluctuated among the locations, building type, and material. The GWP ranges between 50 and 173 kg CO_2e/m^2 for the large office building. In comparison, the range varied to 30 and 254 kg CO_2e/m^2 for medium office. The main driving factors were location, WWR, and materials used in the envelope. In all scenarios, the lowest and highest values are associated with Seattle and Honolulu, respectively. Office buildings in New York City and Buffalo show similar moderate performance in all cases.

In terms of ASHRAE 90.1 energy standard proposed benchmarks, the latest 2019 version suggests the most ambitious criteria for materials to achieve the best performance in new buildings. When comparing with older versions, it provides up to 30% energy and emissions saving compared to the 2007 version and 9% compared to the 2016 version for large office buildings. In medium offices, potential saving reaches up to 49% for the 2007 version and 15% for 2016. With constant office building stock growth in New York City, compared to the 2016 version, ASHRAE 90.1-2019 energy standard has the potential to reduce 5373 GJ energy demand which associates with GWP of 1495 Mg CO_2e.

Results from the analysis show a positive impact of the ASHRAE 90.1-2019 energy standards. The expected savings in growing office building stock in the U.S. depends greatly on the commitment of the stakeholders involved in the governance, construction, and use of these buildings. It also depends on national strategy on the transition to a fossil-free energy system. A fossil-free energy mix and biobased construction material use will contribute to significantly low GWP, while the opposite is expected from the fossil-based and carbon-intensive conventional building material.

Key Words: U.S. Office building; ASHRAE 90.1-2019 energy standard; building envelope; alternative construction material; LCA; GWP

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List of Abbreviations

ASHRAE	American Society for Heating, Refrigerating, and Air-conditioning Engineers
BECP	Building Energy Code Program
BPD	Buildings Performance Database
BIRDS	Building Industry Reporting and Design for Sustainability
BEES	Building for Environmental and Economic Sustainability
CLT	Cross-Laminated Timber
CS	Concrete with Steel-Frame Cavity Wall
CBECS	Commercial Buildings Energy Consumption Survey
DOE	U.S. Department of Energy
EUI	Energy Use Intensity
EPD	Environmental Product Declaration
EIA	Energy Information Administration
GHG	Global Greenhouse Gas
GWP	Global Warming Potential
HVAC	Heating Ventilation Air Conditioning
IE4B	Impact Estimator for Buildings
LBNL	Lawrence Berkeley National Laboratory
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MRR	Maintenance, Repair, And Replacement
MUI	Material Use Intensity
OSB	Oriented Strand Board
PNNL	Pacific Northwest National Laboratory
PBA	Principal Building Activity
SHW	Service Hot Water Demand
SHGC	Solar Heat Gain Coefficient
WWR	Window Wall Ratio

1. Background / Introduction

Building stocks in the world use about 40% of the energy and resources, and they are also responsible for one-third of the total global greenhouse gas (GHG) emissions (Ruparathna et al., 2016). Commercial buildings, among others, consume a relatively higher amount of energy that eventually adds up to a significant amount of life cycle greenhouse gas (GHG) emission that translates into high global warming potential (GWP). The rapid growth of commercial building stock observed through the past few decades in the U.S. impose great demand on the energy sector, which calls for urgent measures for improvement in buildings. The U.S. Department of Energy (DOE) supported several programs, i.e., Building Energy Code Program (BECP), which provides energy efficiency strategies for buildings through standards and laws which provide benchmark values for different types of buildings. The standards developed by the American Society for Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) propose benchmarks for energy use intensity (EUI) per floor area and observes the energy performance of existing and new buildings in different states.

Implementation of the energy standards possesses the potential to control energy demand in current and new building stocks. The effectiveness of the energy standards can manage demand from the forecasted 11.6 billion square meters of commercial floors by 2050 (U.S. EIA, 2020). Such effect on commercial building stock is required as it is expected that energy demand from this type of buildings will outgrow their residential counterpart.

When considering office buildings, in particular, the energy demand is due to heating, cooling, ventilation, lighting, and equipment use. The efficiency of the energy management in such buildings depends on how much thermal mass is balanced inside the building. This means keeping the building at a constant temperature with minimal use of energy. The building envelops play a very important role by separating the building from the outdoor environment. Hence the characteristics of the envelop materials, construction system, and components directly effect on temperature balance inside the building. Researches done previously indicated the potentials of windows to save energy use in buildings (Apte & Arasteh, 2006). In U.S. commercial buildings, it is estimated by Apte & Arasteh (2006) that about 34% of energy use relates to windows. They were also optimistic about the fact that improved windows can halve the energy use in US buildings. Although in another study conducted by Troup and colleagues have found that on the windows in the envelop system may have about a 1% impact on changing energy demand in office buildings(Troup et al., 2019).

In order to estimate energy use and encourage energy efficiency, a set of commercial building prototypes have been developed by Pacific Northwest National Laboratory (PNNL) and Lawrence Berkeley National Laboratory (LBNL). These prototypes include characteristics of existing buildings' features aligned with some threshold control parameters according to the ASHRAE 90.1 energy standard versions. At least 80% of the features match surveyed data published by the Commercial Buildings Energy Consumption Survey (CBECS). The models consider physical aspects (e.g., size, shape, orientation), occupants load (e.g., people per floor area), materials composition for basic construction (e.g., foundation, exterior wall, window, interior wall, roof, etc.), and mechanical systems (e.g., heating, cooling, ventilation, and lighting).

The PNNL prototype buildings have been used to benchmark building performance using the best possible building configuration with theoretical construction materials and mechanical systems. Over the years, ASHRAE 90.1 standards have developed several energy performance standards for both residential and commercial buildings. The objectives of these standards are to provide the necessary parameters to improve operational energy performance in buildings. With regards to the building envelope, the standards have mostly emphasized the thermal performance of glazing materials. It concerns thermal resistance (R-value), conductivity (U-value), solar heat gain coefficient (SHGC), material density, specific heat, etc. The gradual improvements in the prototype buildings are to motivate building designers, engineers, and users to increase energy efficiency and assist in calculating energy saving measures.

Furthermore, accountability of life cycle emissions related to energy use in buildings and materials also calls for attention when considering large growth in the commercial building stock. Especially, when energy related emissions overshadow any other emissions from the buildings. An effective way to manage such emissions would be to reduce energy demand and replace fossil fuels with renewable energy carriers. For materials, most of the environmental emissions occur in the manufacturing and transportation phases. Installation and use in the building have comparatively low share of impact.

Research on building energy use and materials have shown interest in energy efficiency, but very few established methods have been developed to measure case-specific environmental impacts. Especially, when considering windows, very few detailed assessments have been done on the materials used in an improved fenestration system and their impact from any particular energy standard. There is also lack of life cycle process dataset for envelope systems, such as curtain walls that consider both glass and mullion materials. Particularly for commercial buildings, there are some life cycle assessment studies on national building stock, construction materials, and alternative hybrid structures. But very seldom assessments done on the glazing systems included mullion materials with glass used in a curtain wall fenestration system.

1.1. Motivation for thesis project

As the ASHRAE 90.1 energy standards have been used nationally to benchmark energy performance in building in the U.S. This thesis, therefore, investigates the direct and indirect impacts of energy standards on the building and newly constructed commercial building stocks.

The investigation utilizes detailed energy models of two types of office buildings located in four cities with distinctive climatic characteristics. The modeled office buildings resemble majority of the existing office building stock in the U.S. It also selected a set of variables which are most influential for energy performance in buildings and set parameters to match the requirement from chosen energy standard version being studied. It also investigates impacts on annual operational energy use by manipulating window wall ratio (WWR) in the energy simulation models along with changing windows systems, and climatic regions.

To study the energy standard’s effect on buildings, curtain wall systems are considered as building envelop and exclusively evaluates their environmental performance in terms of their global warming potentials (GWP). The GWP is calculated using cradle-to-gate life cycle assessment (LCA) for the exterior wall construction materials (wall, window, insulation etc.), materials transportation and operational energy. The variables considered for the simulation models and environmental assessment are described in detail in the methodology chapter.

This thesis looks forward to answering the following research questions.

1. Which parameters in the building envelope play dominant role in the archetype model?
2. What are the impacts of curtain wall materials for exterior wall and fenestration in the US office buildings?
3. How do energy standards affect environmental performance of a building?
4. How do materials interventions for building envelope affect emissions in different cities?

1.2. Scope of Research

To analyze the impact of energy standards on commercial buildings, two types of offices, large and medium, are selected. The assessment scope of this study provides an opportunity to understand relationship between standards driven threshold values and energy consumption in buildings.

Particularly impacts on building envelop system is investigated thoroughly. Therefore, other structural components are cut-off from the scope of this investigation.

The building models are based on the ASHRAE 90.1-2019 standard, predefined by the PNNL research lab. To study the impact of glazing and material on envelop, two alternative wall-to-window ratios (WWR) and materials composition is considered. These alternatives consist of reduced and increased WWR, improved concrete based envelop with curtain wall using aluminum mullion and low-e double paned window and cross-laminated timber based envelop with curtain wall using wooden mullion and reflexive double paned window. As of the climatic impact, four cities: New York City, Buffalo, Seattle and Honolulu are selected to study their location specific climatic impact on the energy and environmental performance.

The environmental impact assessment is conducted using a ready-made LCA database. It mainly concerns cradle-to-gate assessment for the envelope system which accounts from A1 to A4 life cycle modules and operational energy, B6 module. All impacts are assessed in terms of the functional unit, which is 1 m^2 of gross floor area and one year of operation.

The models are simulated using US DOE developed open access tool EnergyPlus version 9.2. For LCA, mainly consulted EcoInvent Database version 3.7 and product manufacturer's EPD for materials used in the U.S. In case of missing information from these two sources, methods proposed in peer reviewed journal papers were considered. To calculate material use data, BuildME python scripts developed by Heeren (2015) is used.

The functional unit specific results are further scaled to the city specific stock to analyze the impact of different versions of ASHRAE 90.1 energy standard. Chapter 3 describes more about the research methodology used in this thesis.

1.3. Thesis Overview

The thesis contains 6 chapters, starting with the introduction chapter, which contains the broad research context, identified problems formulated in 4 research questions, along with the motivation and scope of this research work.

Chapter 2 contains description of office buildings in the US and current research work on energy standards, commercial building archetype and envelop systems. It summarizes outcomes from previous researches on fenestration system and the parameters which have significance for this study.

Chapter 3 describes methods adapted for the research. It contains 6 sub-chapters explaining model setup criteria, calculations for energy, material and emission model.

Chapter 4 present results from the models and identifies significance of the selected parameters.

Chapter 5 discusses the results in relation to the research questions and verifies the finding based on the existing literature presented in chapter 2. This chapter also reflects on the limitations of this thesis with a suggestion for future research.

Chapter 6 concludes the thesis with key takeaway points and relevance of this thesis.

2. Background

This chapter consists of the information collected through literature review. The following sub-chapters provide details about the commercial archetypes, results from previous researches and the importance of the parameters selected for this research.

2.1. Office Building Existing Stock

To understand the characteristics of commercial building stock condition, Commercial Buildings Energy Survey (CBECS) database provided by the US Energy Information Administration (EIA) is considered along with Buildings Performance Database (BPD). These two databases provide very useful extended information on changing trends on buildings which provides valuable insight to analyze performance of the archetypes developed for this study. The advantage of CBECS dataset is that it was constructed to represent the national building stock, whereas the dataset in BPD is built on complied crowdsourced datasets for real buildings for benchmarking. The large variability of BDP dataset raises question on the representativeness of national building stock. However, recent comparative analysis on the BPD dataset compared to CBECS shows reasonable representativeness of energy use intensity (EUI) data (Walter & Mathew, 2019). Furthermore, the BPD dataset is suggested for energy efficiency trend analysis which also serves the purpose of this thesis work. Although it should be noted that there is over representation of office buildings with some differences in EUI data compared to the national statistics. It is therefore, taken into consideration when comparing the simulated models with existing stock data.

According to CBECS report, the growth of US building stock had already outpaced previous decades in 2012 (CBECS, 2015). The recently published information on 2018 survey data shows a continuity of this trend, and the numbers have grown by 6% along with an 11% increase of floorspace. The report shows that the building numbers increased from 3.9 million to 5.9 million (55%), and the amount of commercial floorspace had increased from 5 billion square meters (51 billion square feet) to 9 billion square meters (97 billion square feet). Among these buildings, office buildings represent 16% of the total number of buildings and 17% of total built floorspace (*CBECS, 2018*).

About 71% of the buildings area 929 square meter (10000 square feet) or even smaller. The CBECS has also identified a median building size which is about 500 square meters (5400 square feet), and the average is 1524 square meters (16400 square feet).

Regarding the construction year of building, CBECS analyzed that most (54%) of the commercial buildings were built between 1960 and 1999 and only a quarter of the stock were built since 2000. According to their report the median construction year of the existing building stock is 1982, which make them about 38 years old. However, the newly constructed buildings tend to be larger than the older ones. The statistics show that older buildings had an average floorspace of around 1200 square meter (13000 square feet) or smaller. In contrast to the ones built since 2000 had an average floorspace of 1765 square meter (19000 square feet) or larger. Hence there is an increase in average floor space than in the number of buildings.

The CBECS dataset samples commercial building from 9 census division across US (Figure 1). Most recent analysis shows that majority of the commercial buildings are distributed to the South (36%) and Midwest (29%). West (21%) and Northwest (14%) has relatively less percentage of buildings. However, floorspace differ a little with the numbers of buildings. In the South, floorspace equals the number of building in terms of overall percentage. But in Midwest and West, it is lower than the number of buildings, i.e. 26% and 20% respectively. Interestingly, in the Northeast, floorspace has higher share than number of buildings, i.e. 16% of overall commercial built area (CBEC, 2018). This means that in the Northeast there are relatively more new buildings than other regions.

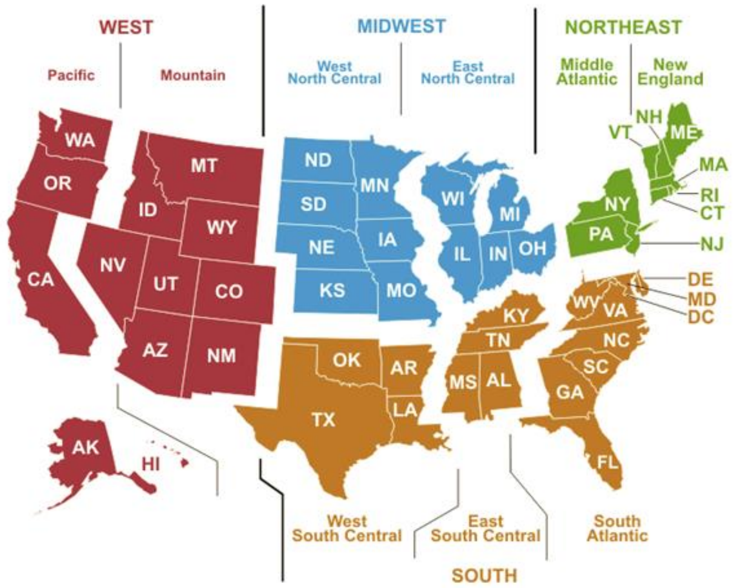


Figure 1 Census divisions for CBECS dataset

Statistics for buildings distribution in terms of the climate regions show that 37% of the buildings are located in “very cold/cold” region and 31% in “mixed humid region.

2.2. Office Building Prototype Model

Commercial buildings prototype models developed by the PNNL research group are built up on several databases and researches characterizing national building stocks (Deru et al., 2011). Works done by Stocki and colleagues (2005); Griffith and colleagues (2007); Huang and Franconi (1999); Huang and colleagues (1991) provided valuable methodological information for the prototype models being used now. These works are consulted to form standardized energy simulation model consisting building attributes, i.e., form, size, external wall construction, thermal zone, HVAC system etc. Since, the objective of these models is to represent 70% of commercial building floor area, CBECS survey data for energy consumption in commercial buildings has been referred to set criteria that represent the actual buildings in average.

The energy models are created using PNNL developed programs as an input file format that can be directly used in energy simulation tools. For each type of buildings, these files consider climate locations based on ASHRAE defined energy efficiency standards reflecting climate specific parameters. The attributes defining each building types depend on the CBECS data, because it provides largest number of records for most typical building types based on principal building activity (PBA). The information is refined with updated statistical database to represent the most updated stock characteristics. Therefore, the reference office building energy models selected for this research, represents characteristics described in sub-chapter 3.2. In terms of location specific characteristics, the PNNL researchers incorporated their analysis on climatic conditions to represent typical cities in each of climate zones in U.S. A brief overview on the four study cities is provided in sub-chapter 2.3.2.

Parameters specifying building characteristics are divided into 4 main categories: program, form, fabric and equipment. Under ‘program’, general information, such as location, total floor area, plug and process loads, ventilation requirements, occupancy, space environmental conditions, service hot water demand and operating schedules are listed. These information are detailed in terms of the form, fabric and equipment selection. The input file contains these aspects with flexible manipulation option based on research objective.

Values specific to fabric and Heating, Ventilation and Air Conditioning (HVAC) equipment change with the choice of the energy standard versions. Emphasis is given on the research results produced by Winiarski and colleagues (Winiarski et al. 2018; Winiarski et al. 2007; Winiarski et al. 2006). Furthermore, for new construction, these input values are proposed by standing standards project committee (SSPC) 90.1 simulation working group and mechanical subcommittee (Deru et al. 2011).

Similar process is also followed to estimate values for occupancy and ventilation information. Engineering assumptions are made to determine plug and process loads and schedules for each of the thermal zones in the building model. The values get updates once more information is obtained. Elevators are modeled as zone load in EnergyPlus. Number of elevators is set according to thumb rule proposed by Beyer (2009). One elevator is modeled for medium office building (4181 square meter floor space) and for large office an additional service elevator is modeled. Input values for service hot water demand (SHW) along with operating schedules to estimate total hot water use comes from research done by Jarnagin and colleagues (2006) and ASHRAE version of energy standard. It should be noted that for all reference models, natural gas water heaters are considered with a storage tank at 60° C. The PNNL research group considered that every day about 3.8 liters of hot water is consumed by an occupant in office buildings which is divided evenly over 9 hours occupancy period. The schedule of operation for HVAC is determined by ASHRAE 90.1 user manual. there were some modifications from the PNNL researchers in order to consider zone-specific equipment use, lighting and plug loads for office buildings (Deru et al 2011).

For reference large and medium office building model, information for program and form comes from CBECS data analysis, Time-Savers Standards for Buildings (DeChiara, and Crosbie, 2001) and experts assumptions. In terms of fabric and equipment, input values are determined by the ASHRAE 90.1 energy standards. It should be clarified here that the term 'fabric' used in PNNL research paper is equivalent to 'building envelop'. Construction types are defined according to the analysis done by Winiarski and colleagues (2007) utilizing CBECS datasets. The models consider flat-roof construction sized according to the building footprint area and defines primary materials with insulation. For both medium and large office, built-up roof with insulation entirely above deck is considered. As for the exterior wall, general construction material reported by CBECS is considered.

Recommended wall construction for newly constructed medium and large office building is steel frame with stucco and precast-concrete panel mass wall with continuous insulation, respectively. To ensure thermal performance of these wall types, ASHRAE standard 90.1 provides a threshold value for heat capacity. For example, a mass wall with a heat capacity more than 143 $MJ/m^2.°C$ should have a material unit weight limited to 4.7 GJ/m^3. This would be for heaviest wall construction. Heat capacity of 102 $MJ/m^2.°C$ can be maintained by light walls with unit weight less than the given value. By using such threshold values, it is possible to model mass wall according to thermal conductivity or U-factor requirements of a selected energy standard. Requirements for U-factors change with energy standards to increase thermal efficiency through building envelop.

The PNNL researchers followed methods developed by Briggs and colleagues (1987) for vintage buildings built before 1980 and ASHRAE standard 90.1 methods for post 1980 and new construction buildings (Deru et al. 2011). While the new construction buildings have to meet different U-values for roof and wall construction, the requirements also fluctuate based on the building's location. It is observed that roof construction requirements are less stringent than it is for the wall and window construction. For mass and steel frame walls, U-values requirements have large difference based on climate locations. Colder regions like Climate zones 5A to 8 require lower U-values compared to the buildings located in climate zone 1A to 4C. Moreover, steel frame walls need to maintain lower U-values than mass walls. For example, allowable U-value for mass wall in climate zone 1A to 5A range between 2.88 to 0.59 $W/m^2.K$. This range is set between 0.70 to 0.36 $W/m^2.K$ for steel frame walls in the same climate zones.

Input variables for window or glazing system construction also considers climatic location. The difference is not in terms of the U-value of the glass material but the solar heat gain coefficient (SHGC). Threshold values are set in accordance with the energy standards, ranging from 0.23 to 0.37 corresponding to climate zone 1A to 5A. Operability of the windows also have impact on thermal performance of the building. But for office buildings, it is assumed that all windows are fixed (Deru et al, 2011).

The prototype models adopt simplified approach to model infiltration for each type of office buildings located in different climatic zones. It uses a fixed infiltration rate to minimize uncertainty in the simulation and to provide an acceptable average annual impact value. Based on engineering assumptions and methods proposed by ASHRA 90.1 standards, the energy model takes account of the air tightness, leakage rate and pressurization conditions on the envelop related to the HVAC systems operation. It follows a threshold value of 2 liters per second and square meters at 75 pa for above ground envelop area (Deru et al, 2011; ASHRAE 2004). Pressurization and depressurization on envelop depends on whether the HVAC and exhaust fans are operating. The infiltration is assumed zero when the building is pressurized in energy models. The PNNL researchers also assume that uncontrolled infiltration in the simulation drop to 25% of 4 Pa when ventilation system is running. In contrast to this, when the ventilation system is inactive, the infiltration is considered to have full leakage rate at 4 Pa. This is modeled at constant air changes per hour (ACH). A constant ACH is assumed to have constant annual effects in different location as well.

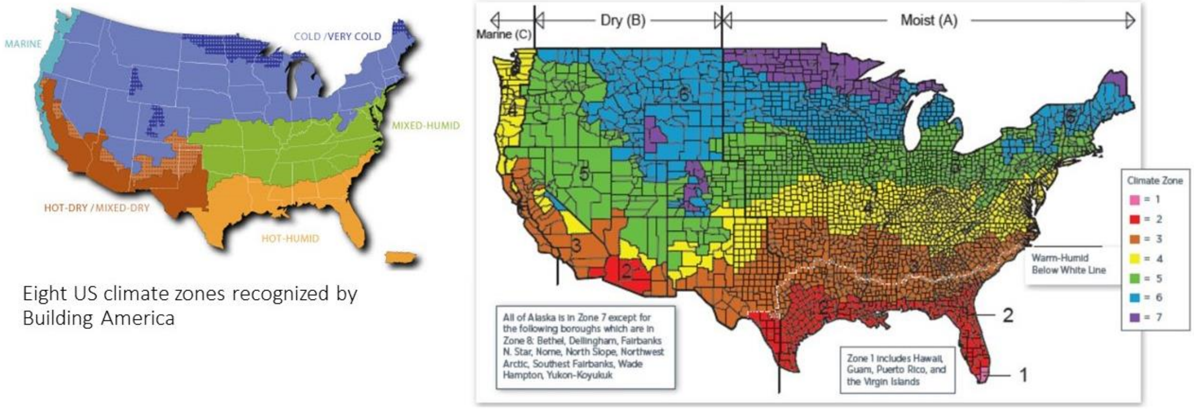
The lighting system is modeled using space-by-space method following the energy standards to determine maximum lighting power density (LPD). While the HVAC equipment sizing is set using the EnergyPlus simulation run with a sizing factor of 1.2 and defined by the design degree day for different locations. Parameters such as nominal coefficient of performance (COP), energy efficiency ratio (EER), seasonal energy efficiency ratio (SEER), boiler and furnace efficiency come from ASHRAE 90.1 standard specified equipment type and size. For fan efficiencies input in EnergyPlus model, the researchers assumed 1.0 as the fraction of motor in the air stream. The models also simplify electric motor specification that should follow national energy policy act. It is assumed that all motors are open, four-pole with 1800 rpm. Further sizing parameters are auto-calculated by the simulation software. The reference building models consider all exhaust fans with 0.65 as mechanical efficiency value and change pressure rise values to meet standard requirements on fan power. The pressure rise values for different air handling units are selected using approximate fan power limitation determined in the standard. Furthermore, cooling efficiency of the equipment is expressed as COP for compressors and condenser fans. The PNNL approach is to use equipment specific information from the standards depending on the type and size from simulation run.

2.3. Climate Region and City

Selection of climate regions and implementation of energy codes in US states … varies performance

2.3.1. Overview of Climate Region

Entire US is divided into 8 climate regions determined by Building America, based on International Energy Conservation Code (IECC, 2012) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) energy standards (Figure 2). These regions are characterized by heating degree days (HDD), average temperatures and precipitation. A brief description of these climate regions is present in this subchapter to relate with the selected study regions in the following chapter.



Eight US climate zones recognized by Building America

International Energy Conservation Code (IECC) climate regions

Figure 2 Climate zones in US – CBECS 2012 (EIA,2012)

- **Hot-Humid** (Zone 1A, 2A, 3A): this region receives more than 50 cm of annual precipitation and can have 19.5º C or higher for 3000 or more hours during the warmest six consecutive month of the year. This can be 23º C or higher temperature for 1500 or more hours during the warmest six consecutive months of the year. The zones 1,2, and 3 corresponding with the IECC map under the moist category (A) below the "warm-humid" line.
- **Mixed-Humid** (Zone 4A, 3A): the annual precipitation of this region is more than 50 cm, and it has approximately 5400 degree days or fewer. The average monthly outdoor temperature drops below 7º C in winter. It corresponds with IECC zones 4 and 3 category A above the "warm-humid" line.
- **Hot-Dry** (Zone 2, 3): this region receives less than 50 cm of annual precipitation and the average outdoor temperature is 7º C throughout the year. IECC zone 2 and 3 are relatable with this region.
- **Mixed-Dry** (Zone 4B): similar to "hot-dry" region, this region also receives less then 50 cm annual precipitation and it has approximately 5400 heating degree days or less. The average monthly outdoor temperature drops below 7º C during winter months. IECC zone 4B (dry) corresponds with this region.
- **Cold** (Zone 5, 6): the heating degree days of this region ranges between 5400 and 9000. The zones 5 and 6 from IECC climate map relate with this description.
- **Very-Cold** (Zone 7): it is defined by heating degree days ranging between 9000 and 12600. IECC zone 7 is related to this region.
- **Subarctic** (Zone 8): this region has heating degree days of 12600 or more. Alaska is the only state with such characteristic, and it is not visible in the map. IECC zone 8 corresponds with this region.
- **Marine** (Zone 3C, 4C): the coldest temperature of this region ranges between -3º C and 18 º C. Warmest months have a mean temperature less than 22º C. in a year at least 4 months reaches higher than 10º C. it has significantly drier summer and wet winter climate. IECC climate 3 and 4 located in the "C" moisture category relates well with this region.

2.3.2. Study Region and City

Four cities are selected to study office building performance using the PNNL commercial building prototype and ASHRAE 90.1 energy standard. The area was randomly chosen based on their uniqueness. Each of the selected cities have distinctive features, i.e. climate conditions, population, energy mix and performance in terms of the U.S. national energy saving program (Table 1).

Table 1 Overview of the selected case study cities

Characteristics	New York City	Buffalo	Seattle	Honolulu
State	New York (NY)	New York (NY)	Washington (WA)	Hawaii (HI)
Climate Region	4A – mixed, humid	5A – cool, humid	4C – mixed, marine	1A – very hot, humid
Population (U.S. Census Bureau, n.d)	8336817	255284	753675	345064
Dominant Primary Energy Source (EPA, 2019)	Natural Gas (36%) & Nuclear (34%)	Same as NYC	Hydro (62%) & Natural Gas (15%)	Fossil Oil (70%)
Adapted Building Energy Standard (BECP, 2021)	ASHRAE 90.1 (2016)	ASHRAE 90.1 (2016)	Washington state energy code 2018	Home rule

2.4. Impact of Energy Standards

Study conducted by the researchers at the Pacific Northwest Laboratory (PNNL) estimated state-level energy savings and CO2 emissions reduction potential from energy codes (Athalye et al., 2016). The research provided methods to compare different editions of the building energy codes along with their adoption in majority of U.S. states and local jurisdictions. The selection of states is based on state-wide adoption and enforcement of the code as well as alignment with the energy standards accepted nationwide. It considered the International Energy Conservation Code (IECC) for residential and ASHRAE standard 90.1 for commercial buildings. The 2010 version of the energy code is considered as the beginning and 2040 as the projected end for the analysis. It concluded with a cumulative primary energy saving of 12.82 quads (or 13.53 EJ) with a CO_2 reduction of 841 million metric tons (MMT) in thirty years. The impact of code activities between 2010 and 2016, the analysis showed approximately 5 quads (or 5.28 EJ) of primary energy savings with about 319 MMT CO_2 emissions reduction.

The researchers used a rolling baseline where savings are calculated using difference in energy efficiency between a new code and its immediate predecessor. The analytical framework in this study used attributes such as, pace of adoption code in states, savings realization rate, annual increase of floorspace in states etc. for incremental savings calculation. And it excluded savings from equipment efficiency mandated by federal rulemaking. Because HVAC and Service water heating (SWHC) equipment efficiency improvement is not correlated to energy code improvement.

Methods applied by the PNNL study provides a guideline to conduct an assessment for energy savings related to energy codes. It provides a way to estimate savings in states with varied code adoption paces. For this purpose a method using the 'code effective date' is described to calculate both expected saving from a particular state as well as compare savings between states. According to this method, a state that has a timely pace of adoption would have less saving compared to the state that has comparatively slower pace of code adoption, i.e. adoption of code within two code cycles or more. For example, if state X adopts 2009 version of code in 2011 and 2015 version in 2016 and stays on the 2015 version until 2022. Then the predecessor for 2009 code for that state would be 2003 version of the code. Later the predecessor for 2015 version would be the 2009 code version. On the other hand, if state Y adopts 2012 version of the code in 2013 and then 2015 version in 2016. The predecessor for 2012 is 2009 for state Y. for the 2015 version this would be 2012 version. By considering these combinations, state X would have much higher savings than state Y. Following this method, other states with moderate and slow adoption would expect higher accumulated savings per floor area.

In terms of floorspace increase per state, the study based on commercial floorspace forecast from AEO 2012 to 2015 database (EIA 2015). It assumed that each state would have roughly an increase of or 92 thousand square meters (a million square feet) every year. The most recent commercial determinations and their associated technical reports describe code-to-code savings in details assessed by Halverson et al. 2014 and Mendon et al. 2015.

2.5. Effect of building envelop

Assessments on envelop systems mostly consider optimization of windows which depends on several factors, i.e. climate region, wall to window ratio (WWR), exterior wall orientation, type of window material and construction system etc. Among these factors, WWR relates to the percentage of glazing area or window on wall surface. A WWR of 100 percent means that the wall is fully glazed and WWR of 10 percent means that the wall has very limited amount of glazed area. Higher WWR allows more visibility and transition between indoor and outdoor environment. So, the building would receive more natural light. On the contrary, large window area means higher infiltration rate which leads to heat loss from the building.

Earlier researches have shown potential energy savings by improving materials quality in building envelopes. Specially for office buildings, where it possesses comparatively higher energy demand for interior lighting, space heating and cooling due to higher occupancy and longer operational hours. Studies conducted by Troup and colleagues analyzed that a better envelope system can reduce energy requirement for lighting, heating and cooling by 10% to 40% (Troup et al., 2019). The savings range also depends on the location of the building.

It is estimated that about 34% of energy use in commercial buildings in the US relates to windows (Apte & Arasteh, 2006). The authors estimated that the installed windows stock in US are responsible for 2.15 quads (2.27 EJ) of heating energy consumption and 1.48 quads (1.56 EJ) of cooling energy consumption annually. Further prediction from Apte and Arasteh (2006) was a saving potential of approximately 1.2 quads (1.27 EJ) through complete replacement of the installed windows with the one of better U-value and SHGC. With improved window technologies the energy saving potentials can even reach up to 3.9 quads (4.11 EJ) (Apte & Arasteh, 2006). These assumptions were made more than a decade ago for all types of buildings in the US. At present, there have been much researches done through energy simulations and statistical analyses (Philips et al., 2020; Hasik et al., 2019; Troup et al., 2019; Susorova et al., 2013).

The statistical analysis done by Troupe and colleagues (2019) examined descriptive statistical relationship between window to wall ratio (WWR) and total annual energy use intensity (EUI) with end-uses directly being affected by envelope performance, including heating, cooling, lighting and ventilation. The outcome of this study only found the most significant impact of WWR on energy performance for cooling energy demand in buildings. They found statistical significance of changing WWR on lighting energy use as well as ventilation energy use but not for heating load. Because these factors rely on the complex interaction of building, occupant and climate characteristics, which do not reflect from statistical data.

On the contrary, energy simulation-based studies focused on physical performance of all building elements, e.g. thermal resistance (R-value), conductivity (U-value), WWR etc. Recently published work by Philips and colleagues have considered studying the influence of WWR with life cycle performance in U.S. office buildings located in 3 different climate zones (Phillips et al., 2020). The assessment was based on several studies, focused on WWR's impact on energy use in buildings.

Li and Tsang (2008) studied office buildings in Hong Kong to understand the impacts of WWR on envelop system and energy use. They found 20% electricity saving potential from lighting with changing WWR (18% and 65%). A predecessor if this study conducted by Chan and Chow (1998) showed that WWR increase accounts for a substantial amount of the total envelop gains This dominates heat transfer through the building envelope with direct influence on cooling systems that account for nearly 60% of the operational energy of such buildings.

In terms of climate relative energy performance, Goia (2016) provided a brief overview of WWR and energy performance in building. The study analyzed optimization potentials in terms of energy savings, daylight autonomy and useful daylight illuminance. Outcome of his study determined that building performance is relatively constant around the optimized WWR. But requires to be within a close enough range to achieve similar results for these performance metrics (Goia, 2016). With similar goals Susorova et al (2013) studied energy performance by altering WWR from 20% to 80% in 10% intervals for various room depths and building orientations. Results showed the lowest operating energy WWR depends on the building's location due to tradeoffs in lighting and conditioning requirements.

Results from a study conducted by Junnila and Horvath (2003) had shown impacts from WWR changes on solar gain, conductive heat transfer, and lighting requirements, influencing the operational energy consumption that accounted for the majority of life cycle environmental impacts in conventional office buildings. It found direct and indirect life cycle impact associated with manufacturing building envelop materials.

Life cycle impacts from materials used in building envelop was assessed by Azari (2014). It found reduced materials specific impact across a series of indicators for reduced WWR in office buildings located in Seattle (Azari, 2014). Furthermore, a sensitivity analysis of design and service decision using whole building life cycle environmental impacts and cost assessment conducted by Hasik and colleagues (2019) found dominance of dominance of operational energy. Their study used US DOE developed medium office build and considered impacts from changing WWR (10%, 33% and 60%), material composition, water use and wastewater management choices. The relevance of these parameters also reflected in the operational energy demand in the life cycle of their chosen building. Furthermore, research conducted by Troup and colleagues which showed that in most optimization scenarios, increased WWR from the 40% baseline scenario has only 1% energy use (Troup et al., 2018).

Outcome from Philips and colleagues (2020) indicated that the energy use in commercial buildings are typically dominated by internal load than envelope loads. Changes in WWR affected electricity consumption by cooling systems (equipment, fans and pumps) which has to balance with solar heat gain from larger window area. Natural gas consumption changed in a same manner. Higher WWR meant larger heat loss, hence demand on heating system increased. Therefore, natural gas consumption increases with increased WWR in colder climate zone. Overall outcome for energy use from this study is that, more than 50% of the simulated electricity use is required for internal equipment, which does not change with varied WWR. While the relative changes are small, the absolute annual changes to energy consumption of the building from different WWR designs are substantial, ranging up to 400 GJ (111MWh) of electricity and 350 GJ (3320 therms) of natural gas over the modeled 60 years. In terms of environmental performance, increased WWR affects materials quantity in envelop system. Consistent with the WWR change, materials demand on wall materials increased and window material demand decreased with reduced window area and vice versa. This means higher manufacturing impacts are associated with changing WWR and materials demand for the envelop system.

Although the results do not show significance change in energy use and life cycle environmental impact associated with operation energy use with changing window-to-wall ratio in building envelop. But they do have direct impact on materials use and emissions related to manufacturing them. Furthermore, one of the aspects in improving the energy benchmark values by the ASHRAE 90.1 standards is to achieve thermal conductivity threshold value specifically in the exterior wall components. Most of the Previous studies have investigated impacts through changing WWR and location using reference materials specific to a particular building. This paves the scope for studying the potentials of alternative envelope construction using improved materials.

2.6. Alternative envelop construction

When considering environmental impact from materials used in the building envelop construction, biobased materials such as wood possesses greater emissions savings potential. Benefits of using such naturally sourced product has been studied by Pierobon and colleagues for midrise commercial construction in the U.S. Pacific Northwest (Pierobon et al., 2019). The research utilized life cycle assessment (LCA) method to compare hybrid structures consisting of cross-laminated timber (CLT) with a conventional reinforced concrete building with identical functional characteristics. They compared two alternative designs for the wall panel, one with gypsum board with structural wood and the other with two additional layers of CLT. Their results showed an average 26.5% reduction in global warming potential (GWP) in the hybrid CLT building compared to the conventional ones. Among the two alternative designs, panels with additional CLT layers proved to have better environmental performance than the other. The results for embedded carbon per square meter of hybrid CLT and concrete buildings were 334 $kgCO_2e$ (with gypsum board panel), 328 $kgCO_2e$ (with additional CLT layers) and 450 $kgCO_2e$ respectively. These values agree with the findings from Simonen and colleagues work on embodied carbon benchmark value for office buildings (Simonen et al., 2017). Compared to the concrete alternative, wood components have an added benefit of storing biogenic carbon for longer time. In this aspect the design alternative with additional CLT layers possess twice as much as the alternative with gypsum board. Although the total primary energy demand remains the same for both wood-based and conventional alternatives.

To ensure similar thermal performance from wood materials compared to the concrete alternative, special consideration must be given to the quality of wood. Glass and colleagues have completed a thorough research on CLT construction for envelop system that provided necessary information to construct energy model with alternative materials (Glass et al., 2013). Their research provided information on thermal resistance (R-value) for typical softwood with different thickness and moisture content suitable for building envelop. The standard R-value ranges from 0.22 to 1.80 $m^2.K/W$ for thickness starting from 25 mm to 200 mm. This values satisfy specifications of generally used structural softwood lumber and their thermal conductivity (U-value) ranging from 0.10 to 0.14 W/m.K (TenWolde et al., 1988; ASHRAE, 2009; USDA, 2010).

Another aspect of considering biobased materials as a substitution of conventional materials has been improvised through a research conducted by Malmqvist and colleagues (2018). Their objective was to identify embodied energy and GHG emission (EEG) reduction strategies in buildings when fossil-based energy consumption decreases through national wide energy efficiency and decarbonization measures. The quantitative study based on European case study building showed a maximum of 77% embodied GHG (EG) reduction potential for timber replacing concrete based elements in buildings (Malmqvist et al., 2018). For new and innovative components used as the main building element, they have reported that timber-concrete hybrid structures contain 30% to 45% less EG than their conventional counterpart (results for A1- A3 life cycle stage).

2.7. Approach to environmental impact assessment

Although life cycles assessment (LCA) for buildings is not very new and several methodologies have been developed based on research interest. But LCA incorporating sophisticated building energy models is still very rare. There are at least three open sourced LCA tools, i.e. Building industry reporting and design for sustainability (BIRDS), Building for Environmental and Economic Sustainability (BEES) and ATHENA Impact Estimator for Buildings (IE4B), which utilizes U.S. specific databases related construction products and processes. But these tools provide very limited scope for users to define input parameters aligned with the energy model. For example, BIRDS inherits all PNNL defined commercial office buildings in its database and provides LCA results to meet alternative levels of operating energy efficiency (J. Kneifel et al., 2019). But it strictly maintains the scope defined by the tool. The tool is useful to make a quick assessment on buildings based on their energy and economic performance utilizing generic data. But it is not an appropriate tool for researchers.

Similar to BIRDS, the BEES online LCA tool is developed to provide a quick overview on construction materials (Joshua Kneifel et al., 2018). It does allow users to select some materials according to their use in building structure with a possibility to compare different products available under the same category. But it is not a suitable tool for extensive research work. Furthermore, the open access online tool has very limited list of products to analyze.

ATHENA IE4B provides much more flexibility compared to BIRDS and BEES. It even allows users to design and build building model using any type of material. But constructing a single building model is quite time consuming with required input for structural systems (Athena Sustainable Materials Institute, 2014). Furthermore, the built model in IE4B may not resemble the ones described by the PNNL prototypes. Hence there is a risk of information gap in the building model developed with ATHENA IE4B tool.

Cubi and Bergerson, in their discussion paper about the necessity life cycle assessment integration with the energy simulation tools to minimize computational limitation associated with life cycle environmental performance of buildings (Cubí & Bergerson, 2010). Their study attempted to provide an integrated environmental assessment method that includes variability of power supply in the analysis. It concluded with remarks on materials database shared between LCA and energy simulation tool to create a validated life cycle inventory (LCI) for buildings. Specifically, to analyze energy related impacts, it proposes to create a power supply system dataset that considers variations in the electricity grid over time. Similar but more advance approach is considered for ‘market activities, production and supply mixes’ in the Ecoinvent v3 database (Weidema et al., 2013). It contains information of reference product that represent consumption mix based on the origin of the product. The dataset provides multiple inputs for the same product from different transforming activities associated with the geographic boundary of the market. Although the Ecoinvent datasets are not directly linked with the energy simulation software. But it does have the quality to reflect on the dynamic product specific activities.

There has been an attempt to improve LCA for commercial building prototypes by Masanet and colleagues (2012). The limits of open access BEES and Athena IE tools were addressed in their work to build a new assessment model called B-PATH. It had the objective to build on publicly available datasets with transparent calculation methodology. The model was also designed to use materials pathways as a collection of major process steps which can be modified by changing process technology assumptions. In the research paper, a case study using low-rise commercial building in California was considered. In terms of construction, a reinforced concrete frame and a steel frame structure were chosen to estimate their life cycle GHG emissions. Thermal mass adjustment for the two building systems were based on EnergyPlus modelling data specific to the climate zone. Outcome of this work showed a total GHG emission for steel-framed and concrete-framed buildings were 14,350 and 14,080 $MgCO_2e$ (Masanet et al., 2012).

In terms of life cycle assessment on office building envelopes, research conducted by Azari (2014) provides an overview of impacts associated with several envelope scenarios on energy and environmental performance in buildings. the study used a hypothetical 2-storey office building with only 335 square meters of floor area located in Seattle with a service life of 60 years. In terms of envelope scenarios, components such as insulation material, window-to-wall ratio, window frame material and double-glazing cavity gas was considered. The life cycle inventory was created using Athena IE for materials and eQuest 3.65 for operational energy use. Results from this study showed life cycle GWP ranging from 467,091 to 503,097 $kgCO_2e$. The lowest impacts were from the scenario which had mineral wool batt insulation and argon-filled fiberglass framed with low-e double glazed window on 40% WWR envelope. The second-best performance was from envelope with same insulation and glazing system and 60% WWR. Highest GWP was found the envelop system that used aluminum as window frame (Azari, 2014).

Robertson and colleagues conducted a comparative cradle-to-gate life cycle assessment of mid-rise office building construction alternatives. They considered a traditional cast-in-place reinforced concrete frame and a laminated timber hybrid system for building envelop. The case study building was a five-storey concrete framed building designed according to Canadian Building Code. For the life cycle assessment, TRACI characterization methodology was used to calculate environmental impacts from the inventory. This study showed that the two design alternatives had the same 3.5 GJ/m^2 energy use associated with cradle-to-gate processes. However, the cumulative embodied energy of construction material was 8.2 and 4.6 GJ/m^2 for timber and concrete design alternatives respectively. Higher embodied energy indicates that the timber alternative has accessible potential energy stored in the material. Overall, assessment of the two material alternatives favor the timber-framed building as it shows a minimum of 14% improvement compared to the concrete-framed one. The maximum GWP saving potential of timber building was 71% as opposed to the concrete building (Robertson et al., 2012).

To evaluate energy use and emissions associated with construction machinery used in commercial buildings Rasdorf and colleagues (2012) conducted a research on nonroad equipment used in construction phase. They considered the fuel use by the machineries in relation to the project schedule, and equipment size. Among the construction activities, site work was identified as the most polluting activity associated with 85% of construction emission (Marshall et al., 2011). The assessment used equipment characteristics from the U.S. Environmental Protection Agency's (EPA) NONROAD model (EPA, 2005). The RSMeans database to estimate duration of construction related activities (RSMeans, 2009). The study found that preliminary construction work on site consumes about 75% of the total construction work which contributes to equally high amount of emission (Rasdorf et al., 2012).

Another study conducted by Hong and colleagues (2014) developed an assessment model for energy consumption and GHG emissions during building construction. It used a process-based LCA and input-output (I-O) LCA model. Their finding showed 95%, 1% and 4% energy consumption associated with material manufacturing, transportation, and on-site construction. These processes contributed to 95%, 2% and 3% of GWP respectively (Hong et al., 2014). In a study, Palaniappan and colleagues (2009) applied a different approach to quantify carbon emission associated with ready-mix concrete transportation and installation. It considered concrete requirement related to structural slab size and transportation distance from concrete plant to site for a truck with a capacity of 10.5 CY (8.03 m^3) for the calculation. The result showed for a 2100 square feet (195 m^2) slab and a 15 miles (24 km) travel distance (concrete plant to site) the truck would require 69 gallons (261 liter) of diesel and emit about 1531 lb (694 kg) of CO2. It provided a reduction scenario with a reduced travel distance. If the plant location changes to 5 miles (8 km) instead to 15 then it is possible to reduce 46 gallons (174 liters) of diesel use and 1020 lb (463 kg) of CO_2 emissions per lot (Palaniappan et al., 2009).

3. Methodology

The framework considered in this thesis work is illustrated in Figure 3. The initial step includes selection of PNNL archetype models representing the most common office buildings in the selected four cities. The selected archetype models for medium and large offices includes all physical, mechanical and climatic attributes of newly constructed buildings. However, detailed construction specific structural and materials aspects are not reflected in an energy model. For example, the archetype models do not inform about columns, beams, load bearing walls etc. Since the purpose of this thesis is to examine impacts only from fenestration system, particularly of curtain wall system, these missing elements do not have impacts in the analysis. As the core objective of energy models were to study thermal performance of the building, special attention was given to materal specific details particularly for the exterior wall surface and fenestration system. For mechanical load for energy use, changes related to alternative materials compositions were automatically adjusted by the EnergyPlus software.

Once the base archetype models were selected, parameters related to the exterior wall and fenestration systems where identified by studying available researches presented in Chapter 2. As a starting point, the building envelops optimization reports published by PNNL researchers were of great help to select the alternative WWR. Since conducting simulations by exploring all possible variations has computational constraints, parameters with the most significant impact were selected to create alternative scenarios.

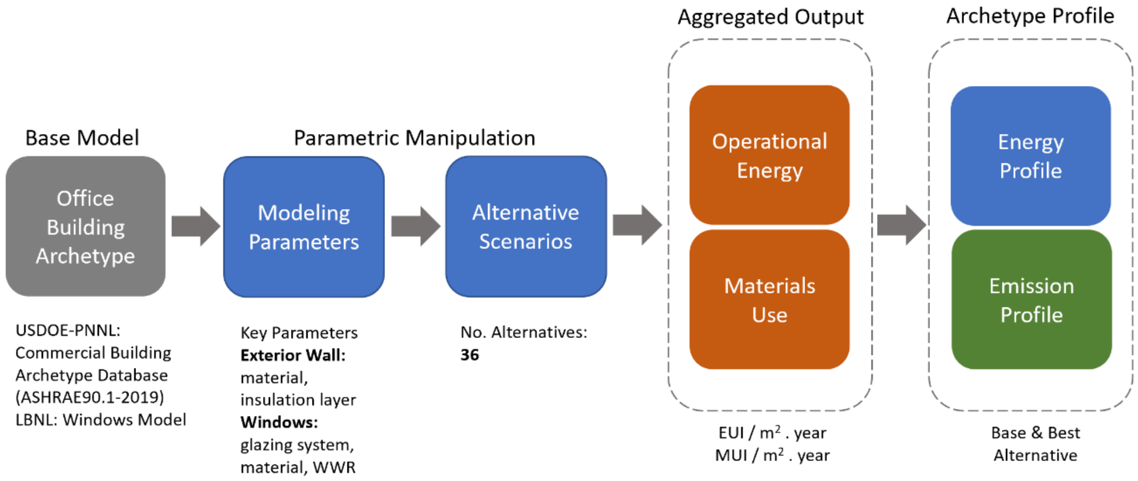


Figure 3 Methodological framework

At the parametric manipulation stage, several alternative materials for exterior wall were tested on the base (archetypes predefined by PNNL) model. Alternations in this step were to explore possible improvements for office buildings both in terms of their energy and environmental performance. The list of tested materials can be found in detail in Appendix *3*. The building components library (BCL) developed by the US DOE has been a useful source to test several wall materials. As for the windows, EnergyPlus material library is used. More about the materials selection process is described in sub-chapter 3.3.

After going through multiple rounds of materials manipulation on the base model, the three best alternatives were selected for further analysis. These alternatives were first assessed through Energyplus energy simulation software to get their annual energy use pattern per gross floor area.

Followed by the energy simulation, materials used in the wall system had to be modeled to estimate material flow per floor area and quantify their embodied carbon footprint. This was done by extracting materials specified in the energy simulation model. There are some assumptions done at this level which is explained in sub-chapter 3.3.

After completing all energy simulations and materials modelling, outcomes per archetype were first aggregated in terms of energy use intensity (EUI) per 1 m^2 floor area and material use intensity (MUI) 1 m^2 per floor area. This helped to create energy and material use inventory for the archetype building which is used to do green-house gas (GHG) emission modelling in the next step.

At the GHG emissions modelling stage, the calculated EUI and MUI are used to estimate the carbon footprint per archetype scenario. Energy and material specific impacts are modeled according to EN 15978 standard (CEN, 2012). The impact relevant to the energy use should be multiplied by the building's operational lifetime and total building area to find its overall environmental impact. At the same time, material specific impacts can be multiplied with the material service life in the building and total building area to find its overall environmental impact from the building's lifetime. This depends on the user's intention on how to use the result and to answer which question.

Details of the methodological steps are presented in the following sections.

3.1. Determination of Energy Standard

The ASHRAE 90.1 energy standard versions have substantial impact on energy performance in buildings. To quantify the improvement in the selected types of buildings and their alternatives, a comparative analysis is conducted between five standard versions. The ASHRAE 90.1 version 2007 is considered as the base and gradual improvements in energy benchmark values come from version 2010, 2013, 2016 and 2019. Since the 2019 version has the latest benchmark values, the savings from the four predecessors are compared with values proposed in this recent code. The EUI/floor area values from the standards are used for calculating the energy savings calculation. For emissions saving potential, methods used to calculate operational energy emission is applied for all of the EUI values collected for each version of energy standard.

3.2. Building Model

The first step of building model is to setup all input parameters of the building archetypes according to the scope of research in building energy simulation software. These parameters include, climate, building geometry, construction materials, windows, shading, HVAC system, internal heat gains, lighting, fuel use, machinery schedule etc. Since this work is based on the collected archetype models, majority of the inputs were predefined for the energy model. Parameters related to building envelope and building location for alternative scenarios were climate, construction materials details and material composition for exterior wall, and window construction along with glass, frame and gas materials details.

More on the selected parameters are described in the following sub-chapters.

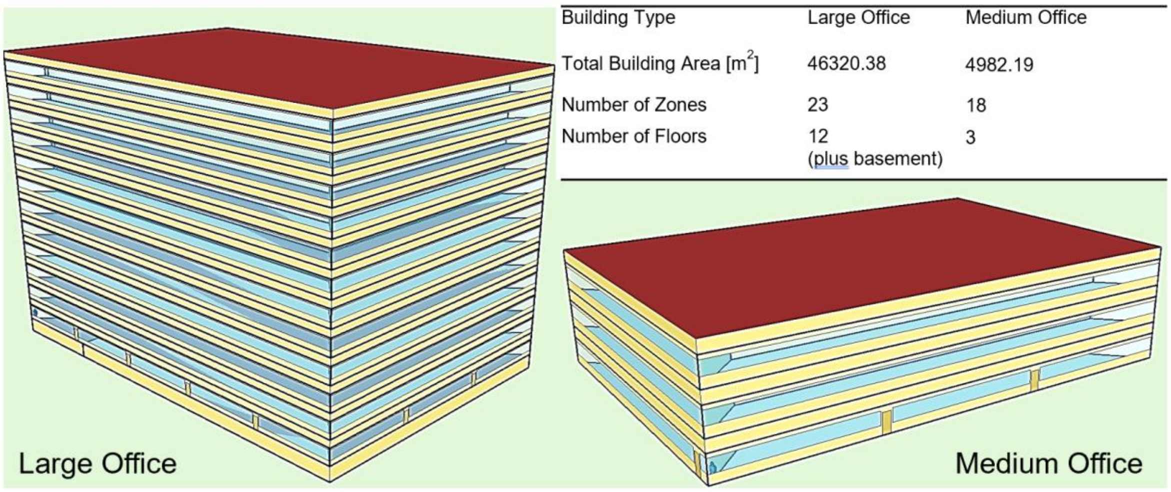
3.2.1. Climate

The location of the archetype buildings in the selected cities have a significant impact on energy use patterns. It depends on the annual outdoor temperature change which defines heating or cooling load inside the building. According to ASHRAE standard (2013) and IECC (2012), the selected cities: New York City, Buffalo, Seattle and Honolulu, studied in this research are located in 4A, 5A, 4C and 1A climatic regions respectively. The climate data in TMY3 Weather Files format, specially developed for EnergyPlus models were used in this study. These weather files were collected from US-DOE supported website for Commercial Prototype Building Models under the Building Energy Codes Program. These files use design conditions based on ASHRAE 2009 climate design data. A list of the used weather files can be found in Appendix *1*.

3.2.2. Building Attributes

The generic building attributes, such as shape, building height, construction type, internal zones etc., are based on the predefined commercial prototype building models by PNNL. Since these prototype building models are developed to represent the majority of the medium and large office buildings in the US, they are used as the reference archetype model. Details of the prototyped model parameters are presented in this chapter.

Two archetypes representing large office (LO) and medium office (MO) were selected for this study. Figure 4 illustrates the building models along with basic information of the two building types. Depending on the location and material composition, eight archetypes per office building type were modeled. To identify the large office building type for each city, they are named as LO-N, LO-B, LO-S, and LO-H. Similarly, medium office buildings were named as MO-N, MO-B, MO-S and MO-H. A summary for all the archetypes can be found in sub-chapter 3.2.6 with an overview of all variable parameters.



Building Type	Large Office	Medium Office
Total Building Area [m^2]	46320.38	4982.19
Number of Zones	23	18
Number of Floors	12 (plus basement)	3

Figure 4 Building Archetype Model

Important to note that the purpose of this study is to investigate impacts from building envelope, particularly of the exterior wall and window materials composition. Therefore, materials used in exterior wall and fenestration systems are explained in detail. Moreover, to quantify materials use from the archetype model, it is important to note that the exterior wall is constructed as a component and it needs conversion to extract material specific information. To avoid complications in the analysis, some assumptions were made to simplify the calculation process. Some materials with insignificant impact such as electric wiring, steel pipes, door handle, etc., are excluded from the calculation.

Shape and Area

Both of the buildings are rectangular. The large office building has a footprint of 73 m by 49 m, and the medium office has a footprint of 50 m by 33m. Both of the archetypes have their long axis aligned on with north-south axis. Each floor is divided into four generic peripheral zones, and core zone. The large and medium office archetype has total 23 and 18 conditioned zones, respectively. The distribution differs between large and medium office. For the large office archetype, each floor has four perimeter zones (29%), one core zone (70%) and one IT closet (1%) (Winiarski et al., 2014). In the large office, there is a datacenter zone at the basement that occupies 28% of the basement floor area. It is quite simplified for the medium office with only perimeter (40%) and core (60%) zones. The perimeter zones have a depth of 4.57 m. Standard floor to floor height is 3.96 m and floor to ceiling height is 2.74 m.

Both large and medium office roof is modeled as a built-up roof with layers of roof membrane, insulation and metal decking. Thermal properties are maintained according to the standard. Non-residential roof insulation is applied entirely above the deck for optimized thermal performance. In terms of tilts and orientations, horizontal or flat roof is considered.

The large office archetype has a conditioned basement that is founded on 200 mm concrete wall, 150 mm concrete slab and 64 kg heavy-weight aggregate. The thermal property for the foundation is set according to the energy codes and standards applicable for the archetype model. The basement walls do not have any insulation and the dimensions are based on floor area. Medium office building on the other hand has a slab-on-grade, unheated foundation. It is constructed with 200 mm concrete poured slab directly on the earth. It is modeled in terms of hypothetical construction facture with required thermal performance from the energy standard.

Other materials for internal partition walls are modeled with 2 x 4 uninsulated stud wall with 150 mm standard wood. The dimensions are based on the floor plan and floor-to-floor height.

Construction Material: Exterior Walls

According to the PNNL research ((D. W. Winiarski et al., 2018) most of the newly constructed large and medium office buildings envelops are constructed with mass wall and steel-framed wall. The exterior wall modeled for large office is constructed with pre-cast concrete panel which consists of three layers of materials (outside to inside): 200 mm normal weight concrete, non-residential insulation (assumed XPS) and 13 mm gypsum board. While for the medium office buildings it is modeled using steel-frame walls with 2x4 steel studs and 400 mm frame gaps. These frames are filled with 4 layers of materials (outside to inside): 25mm stucco, 16mm gypsum board, non-residential insulation (assumed XPS) and 13 mm gypsum board. The selection of materials and layers organized for wall construction are tested to maintain a standard thermal performance. Because the total thermal conductivity (U-factor) of the wall as a component had impact on energy simulation. Lower thermal conductivity means less energy loss from the building.

Alternative Materials

Alternative scenarios developed for each type of buildings include changes in exterior wall materials composition and construction type. Two separate construction for exterior walls is modeled to test energy performance in the large and medium office archetypes. One of the alternatives is considers steel framed concrete wall with cavity insulation using wood fiber insulation board (CSF) (eco-marchant, n.d.) and the other consists of cross-laminated timber (CLT) wall (Glass et al., 2013). The CSF wall is modeled with three layers of materials (outside to inside): 200 mm normal weight concrete, steel framed cavity insulation with wood wool material and 13 mm gypsum board. The CLT wall is modeled with four layers of materials (outside to inside): wood fiberboard, wood fibrebatt, Oriented Strand Board (OSB) vapour retarder and 13 mm gypsum.

Thermal Properties

An important aspect of the newest version of the selected archetypes models is the revised thermal properties of construction materials. The reference archetype model for large and medium office buildings reflect the values estimated by PNNL research group. These values change with climate region. As for the alternative materials, these values are auto-calculated based on the input material characteristics in the energy model. Appendix *2* presents the U-values of modeled materials to compare their varied thermal performance. The ASHRAE 90.1-2019 energy standards provide very ambitious thermal performance from building envelope components. Hence to achieve the suggested u-values, several options for material composition within exterior wall component needs to be explored. Thus, the alternative materials used to test these archetypes provide a good opportunity to find the best fit to meet the current level of ambition for new constructions.

3.2.3. Glazing System

Windows in the reference large and medium office buildings were modeled according to the researches done by LBNL researchers. They were defined in terms of a simple glazing system with thermal and light transmittance properties. It also took account of window fraction, location, glazing sill height, floor area, and aspect ratio. Glazing sill height for large and medium offices are 0.9 m and 1.02 m, respectively. The window type and frame for the hypothetical window are weighted by the U-factor and solar heat gain coefficient (SHGC), and visual transmittance. Similar to the wall materials, the values for U-factor and SHGC are set according to the required ASHRAE energy standards. These values change per climate region. Both of the large and medium office buildings are modeled with 0% operable window area. This is because the entire building is assumed to be fully conditioned.

Alternative fenestration system for large and medium office buildings are modeled with curtain walls using double paned windows with two types of glass materials and two different types of mullion materials. One of the systems use double pane low-E glass (6 mm low-E glass, 3mm air gap, 6 mm low-E glass) with aluminum frame materials. Another system uses double paned reflexive glass (6 mm reflexive glass, 3 mm argon gas, 6 mm reflexive glass) with wooden frame materials. Appendix *3* provides a summary of thermal properties for both hypothetical windows and alternative glazing construction.

3.2.4. HVAC system

The HVAC system is modeled according to PNNL’s CBEC study and ASHRAE Standard 90.1. The large and medium office has separate requirements due to the space volume and area. Hence the basic setup parameters are described separately below.

Large office

An efficient air barrier system is modeled following the energy codes and standards requirements using PNNL developed infiltration modeling guidelines. Peak infiltration is modeled at the rate of 0.2016 cfm/sf of above grade exterior wall surface area which is adjusted by wind effect. This is when the fans are turned off. During off peal, 25% of peak infiltration rate is allowed when fans are turned on.

The heating system consists of one gas-fired boiler. While the cooling system used water-source DX coil with fluid cooler for datacenter in the basement floor and IT closets in other floors. Two water-cooled centrifugal chillers are used for the rest of the building. In terms of distribution and terminal units, VAV terminal box with damper and hot-water reheating coil are used for most of the floor areas. For datacenter portion of the basement and IT closets, CAV units are used.

Sizing for the air conditioning and heating units were auto sized to design day. In terms of HVAC control, temperature for the thermostat setpoint is modeled at 24°C cooling/ 21°C heating. The setback temperature is set at 27 °C cooling/ 16°C heating. Supply air temperature is at max 43°C and min 11°C. Chilled water supple temperature is 7°C and hot water supply temperature is 82°C.

Primary chilled water (CHW) pumps are modeled at constant speed and secondary CHW pump is set at variable speed. For IT closet water loop heat pump is set at constant speed. Cooling tower pump is set at variable speed. Service hot water (SHW) pump is set at constant speed and hot water (HW) pump is set at variable speed. The pumps are specified according to ASHRAE Standard 90.1 model enhancement requirement.

Open cooling tower with two-speed fans, two-speed fluid-cooler for data center and IT closets are modeled for the simulation. Power requirement is auto sized by the software.

A main water heater with storage tank is selected for SWH. It is fueled by natural gas. Tank has a capacity of 300 gallons (1364 liter). Water temperature setpoint at 60°C. Water consumption depends on the operation schedule.

The lighting average power density is set at 10.8 W/m^2 in each zone. The schedule for lighting is according to occupation schedule. The daylight control and occupancy sensors are set according to energy codes and standards.

Medium office

The air barrier system is modeled in the same way as modeled for large office archetype. An additional infiltration through building entrance is also considered.

Heating and cooling system for the medium office is modeled with gas furnace inside the packaged air conditioning unit. VAV terminal box with damper and electric reheating coil is used in distribution and terminal units. Both air conditioning and heating are auto sized to design day. Efficiency of the system is based on energy code and standard requirement. For air conditioning the minimum equipment efficiency for air conditioners and condensing units. And for heating the minimum equipment efficiency for warm air furnaces.

For HVAC control, the thermostat setpoint is modeled at 24°C cooling / 21°C heating. While the thermostat setback is modeled at 27°C cooling / 16°C heating. Supply air temperature is set at max 40°C and min 13°C. It should be noted that the temperature setpoint reset may be required by codes and standards.

Service hot water (SWH) pump operate at constant speed. They are first estimated based on circulation flow and then adjusted based on modeled design flow. The power requirement is auto sized. There is no requirement for cooling tower. The SWH has storage tank and it runs on natural gas. Thermal efficiency is determined by the energy codes and standards. Tank volume is 100 gallon (455 liters) and water temperature setpoint is 60°C. water consumption depends on operational schedule.

The lighting system is modeled in the same way as large office archetype.

Other – miscellaneous

The large office building has 12 elevators with a traction motor. Peak power consumption by the motor per elevator is 20370 watts. This leads to exterior heat gain to building. The medium office has 2 hydraulic elevators which requires 16,055 watts. This leads to interior heat gain to building. Both types of elevators have 161.9 watts power required for fan/lights at the peak.

Internal Heat Gains

Internal heat gains are dependent on lighting, equipment use and occupants. The number of occupants per area and schedule for occupancy has direct impacts on it. For example, required hours of using the office facility in a day connects with the operational schedule for the lighting and HVAC systems. Thus, the operational schedules are connected to working hours leading to internal heat gains in the building. So, the peak heat gains are expected during the working hours (from 8 AM to 10 PM weekdays in summer). The schedule inputs are done in binary (0,1).

The large office space has about 18 m^2 designated for one person. The entire building has modeled for 2429 people in total. For medium office 19 m^2 is designated for one person and it is modeled for a total of 268 people.

3.2.5. Lifetime

From various literature and report on archetype buildings and materials.

The service life of office buildings are expected to be 41 years (J Kneifel, 2012). There is an accepted assumption for insulation and windows lifespan which is greater than 40 years (Kneifel, 2012; Whitestone, 2008). In terms of maintenance and repair, insulation is assumed to have no such requirements but for windows at least 1% of windowpanes need to be repaired annually. For heating and cooling units, there are different service life along with maintenance and repair rate depending on climatic region. It can range between 4 to 33 years for repair and 13 to 50 years for replacements. A study done by Whitestone (2008) shows that a 586 W gas boiler needs repairing every 19, 8, and 7 years for climate zone 1, 4 and 5 respectively. As for 17.6 kW (5 ton) rooftop, multizone air conditioner the repair rates vary from 9, 15 and 16 years for the three climate zones.

These assumptions were done to estimate costs associated with building maintenance, repair, and replacement (MRR). It would be safe to also assume the same to calculate life cycle emissions from MRR per components being studied in this research. Although in terms of comparability for the repair rates and building types, Kneifel (2012) has reported discrepancy between the findings from Whitestone (2008).

3.2.6. Archetype Definition Summary

Based on the office building descriptions presented above, seven key parameters are considered significant for energy and emissions performance related to building envelop. Their impacts on energy use intensity in the building is observed through changing value under these parameters in energy simulation model. The list of variables is summarized in *Table 2*.

Table 2 Office building archetypes variable parameters overview

Variable Parameter	Large Office (LO)	Medium Office (MO)	Comment
City (used short name)	New York City (N), Buffalo (B), Seattle (S), Honolulu (H)		
WWR	20%, 40%, 90%	15%, 30%, 70%	
Base Exterior Wall (B)	Concrete Mass	Stucco	
U-value [W/m2-K]	0.51, 0.59, 0.288	0.31, 0.36, 0.70	Changes with climate region
Alternative Wall 1: Concrete with steel frame cavity wall (CS), U-value [W/m2-K]	0.34		
Alternative Wall 2: Cross laminated timber (CL), U-value [W/m2-K]	0.285		
Theoretical Window U-value (base)	2.045, 2.843		Determined by the location
Alternative Window 1: Low-E with Aluminium frame	1.779 (window), 0.17 (frame)		
Alternative Window 2: Reflecsive with Wood frame	2.01 (window), 0.132 (frame)		
SHGC	0.355, 0.374, 0.232		Determined by the location
Building Service Life	41 years, 36 years		Kneifel (2012), CBECS Survey (2018)

3.3. Energy Model

The energy simulation is run on EnergyPlus version 9.2.0 as mentioned in previous chapters. In this study the most updated ASHRAE 90.1 (2019) models for the selected four cities were used. It is done firstly to find performance variance for the ambitious theoretical models with some of the materials used in the construction sector. Secondly to learn about their environmental performance in terms of operational energy use. And finally, to find out possibilities to apply such modification in existing building stocks.

Data required for EnergyPlus were collected as a package for the reference medium and large office archetypes from open source US-DOE’s database on PNNL commercial model. As the 2019 version of ASHRAE 90.1 energy standards are studied, all archetype input data stored as input data file (IDF) were collected. The IDFs are easy to read and manipulate the parameters mentioned earlier in EnergyPlus IDFs.

Attributes related to the building’s physical characteristics, location, materials composition, fenestration system, occupation and mechanical system is defined as mentioned in the building model chapter. Each of the building types (large and medium office) has one reference or base archetype IDF for the four cities and two alternative archetype models with alternative materials composition. Furthermore, each archetype have two additional alternatives in terms of wall-to-window ratio. This leads to a total of nine IDF models per building type and city.

One of the simplified approaches for defining building geometry in the energy model is to use zone multipliers. This feature is used for multiple floors that has same floor size and internal gains. So instead of modeling 10 floors, all it requires is to model one floor in detail and add number floors with same configuration as multipliers in the model. This saves time without compromising quality of the result (Kneifel, 2012; Michałowska , 2020; Big Ladder Software, n.d).

The thermal properties of exterior wall and fenestration materials were modeled with reference to Building Component Library (BCL, n.d.), EnerpgyPlus materials database, and literature on the alternative wall and fenestration systems. The thermal performance per envelope components was set according to the reference energy standard. Additional calculations required to define the alternative fenestration systems frame materials input parameters. This required adjustment suggested by the EnergyPlus guideline (Berkeley et al., 2019). Curtain wall specification documents are consulted to define the aluminum and wood mullions (Aluminum & Angeles, 2012).

HVAC system is modeled according to the reference archetype standards. The reference system is used as an ideal for all alternative scenarios. The end energy use per floor area including heating, cooling, lighting and ventilation, is calculated by EnergyPlus. The useful results from the simulation are documented for further calculations.

3.4. Materials Model

The US office building generic materials composition mainly refers to CBECS survey data. Hence the reference model includes typical construction materials used in buildings. The materials used in the envelop is grouped according to the ASTM UNIFORMAT II (Uniformat, n.d.). The building envelop is defined as “Shell” which has three elements: superstructure, exterior closure and roofing. According to the scope of this research, materials used in the exterior closure is considered. Under this element there are three individual elements: exterior walls, exterior windows and exterior doors. Materials modeled to from these three individual elements are of interest for this study.

For the purpose of this study, only the materials specific to exterior wall and fenestration system is extracted for further modeling and calculation. Figure 5 illustrates data processing procedure to create the building envelop material inventory.

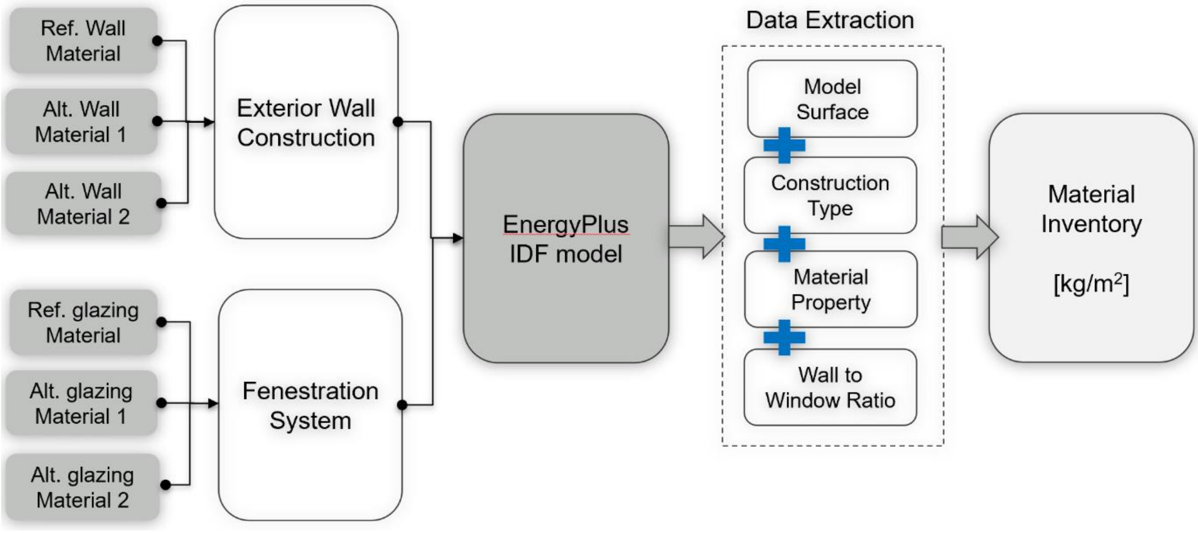


Figure 5 Material inventory development process

As described in the building and energy model process, the IDF file per archetype consists of information about the exterior wall and fenestration system. These two components are described in terms of the physical properties of the material (roughness, thickness, conductivity, density etc.). It also includes material specific information on thermal, solar and visible absorptance. For some lightweight materials, i.e. insulation, an alternative input is considered in the EnergyPlus IDF editor. In this method, input includes only the roughness, thermal resistance, along with three aspects of absorptances. The theoretic windows in the reference models use only simple glazing properties – U-factor, SHGC and visible transmittance. The alternative windows with frame materials include much more details about the materials thickness, density, conductivity, thickness, etc.

Construction of exterior wall component and fenestration system defined in the IDF file includes both materials considered per component and the surface type. So once the wall area and orientation gets defined, it requires construction-specific input per component and climate for thermal performance of that wall based on its location in the building. A similar is considered for windows applied to a specific wall.

Since the IDF files contain detailed information about the materials of interest in the archetype model, it becomes sensible to apply material extraction directly from the IDF files. For this purpose, python based BuildME framework developed by Heeren (2019) is used to calculate building materials from EnergyPlus IDF files. There were some modifications required in the framework to include newly created archetype models. Especially the changes related to WWR and material use per wall and fenestration surface area has significance in the output materials inventory. These modifications can be found in GitHub repository for developments in the BuildME framework.

While running the data extraction process, several materials such as insulation, glass and air for windows etc., defined in the IDF file using only their thermal properties, needed additional calculation. This is because the BuildME framework considers the material thickness, density and conductivity to do the calculation from IDF and converts them into material mass per floor area expressed in Kg/m^2. Additional material specific information is listed in Appendix *6*.

The calculation for the materials used in the fenestration system, i.e. glass panels and mullions used in the curtain wall needs additional information to create the final inventory. While the glass panels are quantified by the density, thickness and material requirement per glazing area, the frame material is quantified based on engineering assumption relative to the glazing system (Michałowska, 2020; ABNT, 2005). For example, if 1m^2 of glazing requires 28 kg glass, then for every 1 kg of glass there is 4 kg of aluminum or 6 kg of wood is required (Association, 2020). One more step is required to convert the units to quantify materials needed for 1m^2 of floor space.

It should be maintained that some details of building construction materials, such as insulation used in foundation structure, floors lab, roof and interior wall do not fall under the research scope. To avoid error in the materials models in BuildME, missing and out-of-scope information are treated with null values. Table## in the appendix summarizes the avoided materials in this model.

The final result from all reference and alternative models per building type can be consulted from Appendix 4 and Appendix *5*. The material intensity per floor are does not change in the cities, but they change per window-to-wall ratio. Furthermore, the direct impact from material intensity per construction type is expected in the environmental performance per archetype model. This is because if a building requires more material, i.e., concrete per floor area, then more embodied carbon and energy will be added to its profile.

3.5. Emissions Model

Describe about the life cycle stages considered in the study and describe the calculation procedure one after the other. Also, which ones are considered, and which are not considered and why not.

The modeling parameters detailed in previous chapters provides necessary information to quantify greenhouse gas emission from the archetypes developed in this study. For this purpose, component specific life cycle assessment (LCA) is considered following the European Standard EN 15978. This standard is adopted by most researchers to define scope and calculation methods for building specific products, processes, and life cycle stages. Figure 6 shows the life-cycle stages identified according to EN15978 with defined scope and modification related to life-cycle impact aligned with the motivation of this thesis.

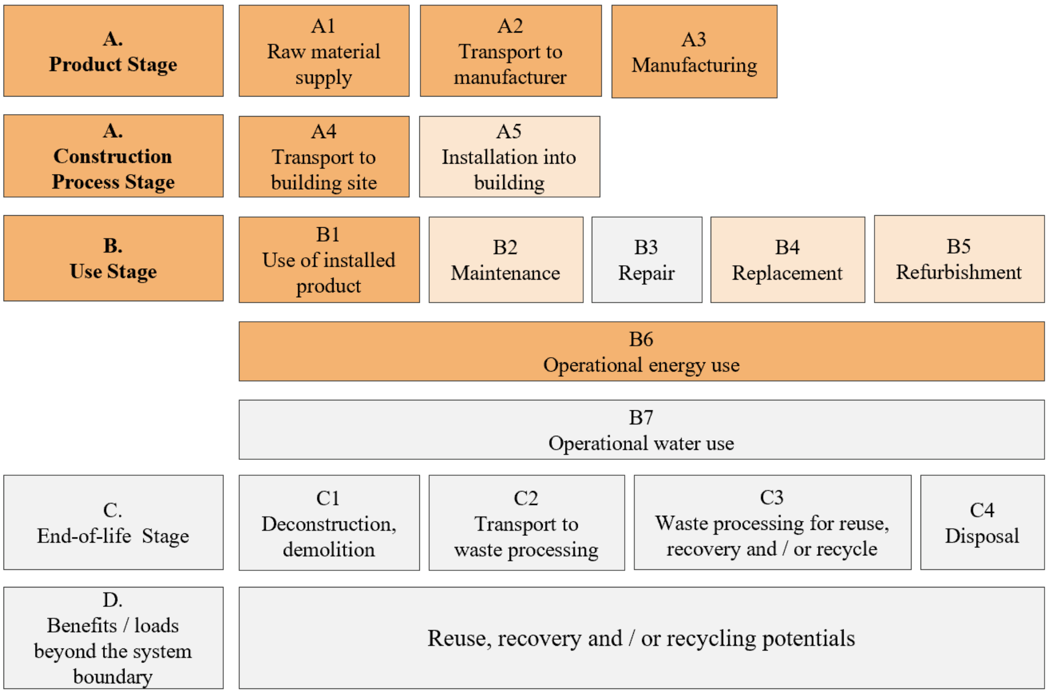


Figure 6 Construction products life cycle stages (modified from EN 15978)

The life cycle stages marked in dark orange are selected to calculate emissions from the archetype models. The light orange ones are marked because they have some effect related to the material specific emissions that can be considered depending on the purpose of analysis. System boundary is defined according to the modules defined by the standard. Functional unit considered per material and energy use in the archetypes is 1 m^2 gross floor area of building during 1 year of operation. All emission flows are considered up to their midpoint impact category and limited to Global Warming Potential (GWP). The ReCiPe midpoint method (H) developed GWP100 metric is used from readymade life cycle inventory database, Ecoinvent v3.7.1. For most of the products, life cycle processes with allocation cutoff criteria is used to collect the emissions multiplier. Priority is given to the datasets which represent the study regions. In case of missing region-specific data, generic industry specific datasets are selected. Appendix 8 and Appendix 9 summarizes all life cycle processes used in this study.

Generic formula for calculating environmental impact per life cycle process is as follows.

$$E_i = GWP_i \cdot q_i \qquad (1)$$

Where,

Ei = Total environmental impact of item i
GWPi = total elementary global warming impact of item i, unit expressed in “Kg CO_2e / Functional Unit”
q_i = quantity of item i required for the functional unit

Emissions per life cycle module are calculated using this generic formula. The GWP impact matrics per process need some normalization to relate with the functional unit of this study. For example, the market for concrete production in the Ecoinvent database uses reference flow of 1 m^3 and the GWP100 value associates with per m^3 of concrete. To normalize this value according to the functional unit of 1 m^2 building floor area during 1 year of operation, the reference flow of 1 m^3 concrete needs to be converted according to the material flow unit of Kg/m^2. This is also required to calculate the q_i per item used in the archetype model.

It is also important to mention that the emissions associated with module A5 is not considered in the emission model. This is because, researches show that emissions associated with products installation has less than 5% of emission occurs at the installation phase (Frey et al., 2010). Furthermore, the wall and window panels are assumed to be prefabricated at the production site. Therefore, installation at site do not have impact on emissions associated with the envelop systems considered in this study.

Following sub-chapters provide details of the calculation procedure per life cycle module and process.

3.5.1. Modules A1 – A3: Materials Production

Processes associated with manufacturing or production of construction materials fall under life cycle module A1, A2 and A3. The global warming impacts from this modules of material ‘i’ is calculated using the generic formula in equation 1. GWP_i calculation of each material in the wall and window system uses the process specific dataset presented in the Appendix *8*. The total quantity of the item is listed in Appendix 4 and Appendix 5.

This study utilizes ready-made inventory datasets specific to material production process under this module. It includes ‘cradle-to-gate’ unit processes according to EN15978 standards (CEN,2012). The selected inventory under this module also considers transportation-related emissions but until manufactures’ site. Hence the transport related emissions from the manufacturer’s site to building site associated with module A4 is explained in sub-chapter3.5.2.

The emissions inventory dataset selected for the production processes are based on quality of data that is representative of the process relevant to the scope of study. Priority is thus given to the best available and acceptable dataset consisting of manufacture-specific activities of the item being assessed. The production processes datasets represented by the Ecoinvent database V3.7.1 in the form of “market for production” has an ideal method of calculating the typical consumption of materials per product (Weidema et al., 2013). This also includes average transportation values and losses in trade and transport. For the dataset selection, preference goes first to US specific dataset, then to Northern American industry specific average data and then to global generic production.

While most of the materials are quantified from EnergyPlus IDF files, curtain wall frame materials needs an alternative approach to extract the material intensity data. It follows the same method as the material model to create the final emission model. But it depends on four types of process specific emissions data to reach the desired value. For this purpose, individual elements production process life cycle inventory data is collected. Individual elements include, glass in the double glazing panel, aluminum and wood for the window frame or curtain wall mullion. Production processes selected for these elements are "market for glazing, double, U<1.1 W/m2K, Laminated safety glass, GLO", "market for window frame, aluminum, U=1.6 W/m2K, GLO", and "market for window frame, wood, U=1.5 W/m2k, GLO" from Ecoinvent 3.7.1 database. Reference flow for Kg material required for 1m2 of glazing area is known from the dataset description. This is then normalized to the functional unit of Kg/m^2 floor area. With this inventory it is possible to calculate GWP100 of double-glazed window with aluminum frame and wooden frame. The results show that 1 kg of aluminum frame have 6 times higher GWP than 1 kg of wooden frame. This finding is used to estimate emissions associated with wood supported curtain wall system.

To quantify curtain wall system specific emission, EPD declared by EFCO, a US based curtain wall manufacturer, taken into account (EFCO, 2017). It should be mentioned that this EPD suitable for traditional curtain wall system with aluminum mullion. The data is cut-off to cradle to gate emissions per m^2 curtain wall system (mullions) and normalized to the functional unit of this study. The result is combined with the results found for glazing to create final emission inventory for aluminum mullion supported curtain wall. For wood supported curtain wall, based on calculations from wooden window frame, a multiplier is used with the results from aluminum supported curtain wall.

3.5.2. Module A4: Transportation Manufacturer to Building Site

All emissions associated with transportation of products from manufacturer's site to the building site fall under this module. For this study, it is assumed that most materials are produced in the same city or state. And the mode of transportation from the manufacturer's facility to the building site is by road, i.e., commercial truck or lorry. For the sake of study, a random building site and product source is selected to estimate transport related emissions. Table *3* presents the travel distances considered per city and product.

Table 3 Travel distance for products transported to the building site in study cities

Product Category	Travel Distance [km] (City)
Fenestration (curtain wall, door, window etc.)	56 (N), 635 (B), 10 (S), 29 (H)
Ready-mix concrete	32.4 (N), 646 (B), 49 (S), 40.4 (H)
Lumber and other construction products (wood board, stucco etc.)	12 (N), 700 (B), 6.2 (S), 39 (H)
Insulation materials	193 (N), 570 (B), 22 (S), 15.2 (H)

The location of building site and product sources is based actual location of commercial area and construction material producer site in each of the study city. The distance is measured using Google map travel route data. In case of a missing production site, a construction material supplier's location is considered. Site for the office building is justified on the fact that most of the buildings is situated in the commercial hub of a city. Product categories are developed according to the material inventory. The location of producer per product is selected based on the most popular manufacturer in the city. This information is collected based on Google map. Travel distances for 3 out of 4 cities more most of the products are below 100 km except for Buffalo. This is because it is assumed that Buffalo and New York City rely on the same material producers.

Regarding ready-mix concrete, assumptions follow methods proposed by Palaniappan and Stecker (2009). A concrete mixer truck with a capacity to carry 1830.84 kg ready-mix concrete is considered to estimate emissions associated with this module. The elementary flow for the emission takes into account diesel consumption per kilo meter and Kg of CO_2 emitted per kilo meter travelled. This needs recalculation in terms of the functional unit considered in this study. This may raise oversimplification of emissions from ready-mix concrete transport vehicle. Generally, this is calculated in terms of horsepower (hp) per hour unit when calculating construction site emissions from construction machineries/equipment. But for the scope of this study, transportation from manufacture site to construction site has direct relation to emissions associated with exterior wall system.

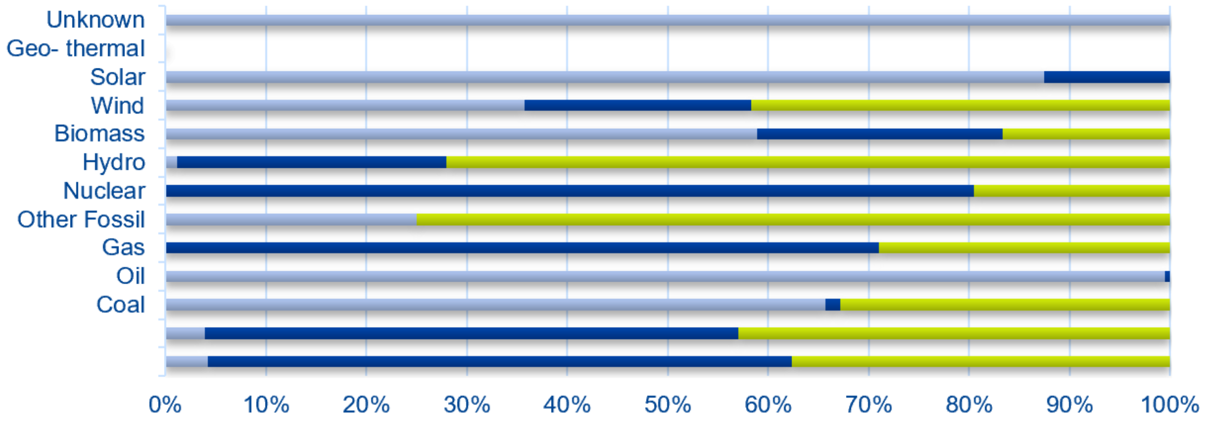
Emissions inventory for the rest of the products uses Ecoinvent 3.7.1 dataset for "market group for transport, freight, lorry, unspecified, GLO" process, allocation cut-off by classification. The GWP100 metric provides values for 1 ton of freight travelled 1 km. This is adjusted to the functional unit and then the total emissions are calculated using the equation 1.

3.5.3. Module B6: Operational Energy

Emissions associated with energy used throughout the lifetime of the building is considered in this module. EnergyPlus simulation results per archetype building and functional unit form the chapter 3.3 provides energy flow data to calculate emissions for this module. The energy data consists of energy used for lighting, equipment, cooling and heating and expressed in kWh/m^2.year. These values are used as q_i in equation 1 to calculate the total GWP100 value from energy use. The impacts are related to the type of fuel used in the building. As described in chapter3.2.4, electricity is used for most of the functions, while natural gas is used in some regions for space heating.

The LCIA dataset for elementary impact GWP_i is created based on the regional electricity mix. The energy mix is the percentage of primary fuel type for energy production. Different states in the US uses different fuel type to produce energy. Figure 7 shows the mix of primary fuel types for energy production in the states where the study cities are located in.

The US Environmental Protection Agency (USEPA) published data for state-level emissions associated with electricity grid is considered (USEPA, 2019). It provides GWP100 values calculated according to the fourth IPCC assessment method (EPA, 2018). Emissions associated with natural gas is calculated using fuel combustion values and GHG emission factor published by the USDOE. The GWP100 value for the emitted GHGs is calculated using the CO_2e value provided by IPCC (IPCC, 2007). Appendix *9* summarizes the normalized to functional unit values for the final emission model for operational energy use.



			Coal	Oil	Gas	Other Fossil	Nuclear	Hydro	Biomass	Wind	Solar	Geo-thermal	Unknown
▨ HI	3,872	9,749,	13.4%	70.4%	0.0%	0.1%	0.0%	1.0%	5.3%	5.4%	2.8%	0.0%	1.8%
■ NY	53,439	131,56	0.3%	0.4%	36.2%	0.0%	34.1%	23.0%	2.2%	3.4%	0.4%	0.0%	0.0%
🟩 WA	34,585	106,46	6.7%	0.0%	14.8%	0.3%	8.3%	62.0%	1.5%	6.3%	0.0%	0.0%	0.0%

Figure 7 Energy mix in selected Hawaii (HI), New York (NY) and Washington (WA) (USEPA, 2019)

3.6. Building stock assessment method

The benchmarked EUI values associated with the ASHRAE 90.1 energy standards version 2007, 2010, 2013 and 2016 were collected in relation to large and medium office prototype buildings. Each of these EUIs were compared with the 2019 version in terms of their energy use associated emissions. The EUI comparisons were straightforward, while for the emissions, GWP multipliers used to calculate emissions for the cities were used. The calculation for potential savings using the current standard in contrast to the predecessors was analyzed using a modified version of the method developed by Athalye and colleagues (2016).

To analyze energy use characteristics in the new office building stocks in the four study cities, a general assumption has been made. Tt is assumed that at least 92000 square meters of office floorspace is added yearly in each of these cities. Among this, 20% is large office and 80% is medium office. This results in 18400 square meters of floor area corresponding to large office characteristics and 73600 square meters of floor area corresponding to medium office building model. In reality, this might be overwhelming for small cities like Honolulu or too small for large cities like New York City. For the sake of analysis, as suggested by Athalye et al. (2016), this estimation would provide less error than relying on incomplete dataset such as CBECS and BPD. The total built area is then multiplied with the EUI values and GWP multipliers, corresponding to each of the standard versions and cities. Differences between the processor and current EUI benchmarks are calculated using equation 2 &3.

$$E_s = E_{pi} – E_c \qquad (2)$$

$$G_s = G_{pi} - G_c \qquad (3)$$

Where,

‘E_s’, ‘E_{pi}’ and ‘E_c’ indicates to energy saved, energy use from ith version of predecessor and energy use from current version of the standard, respectively. Similarly, ‘Gs’, ‘Gpi’ and ‘Gc’ indicates to GHG saved, GHG emission from ith version of predecessor and GHG emission from current version of the standard.

4. Results

Findings from the archetype models are presented here, corresponding to the methods described in previous chapter. The results are presented chronologically, starting with outcomes from energy simulation model, followed with the materials model and emissions model. Sub-chapter 4.4 provides results from comparative analysis conducted on different versions of energy standards and their potential to save energy use and associated emissions in new building stock.

4.1. Energy Modeling Results

As mentioned in the methodological framework in Chapter 3, energy simulation for 36 alternative office building archetypes were run using EnergyPlus version 9.2.0 software. The simulation results provided thorough insight of the two-office building's energy consumption pattern in a year. Since the software generated summary report contained thousands of output values, only the end use energy use per floor area , quantity and type of fuel used per HVAC system, and thermal performance summary associated with building envelope were extracted based on the interest of this research.

As the energy models consider the buildings to be fully conditioned, the end energy demand is mainly caused by equipment and types of machinery required for HVAC systems. The result showed substantive variance in the distribution of energy end use per building systems with location and building type. The highest percentage is consumed by the 'Receptacle equipment' followed by 'Space Cooling' and 'other miscellaneous equipment'.

Depending on the location, large office buildings in Honolulu requires the most energy for space cooling, almost 20% of total consumption and Seattle requires the least, about 5% of the total. In New York City and Buffalo utilizes about 9% and 7%, respectively of total energy used in the building. In terms of receptable equipment's share of energy use, buildings in Seattle utilizes about 56% of the total energy and in Honolulu the share is about 47%. Buildings in New York City and Buffalo has about the same percentage, 53% and 54% respectively. Share of energy used by components in each of interior lighting, space heating, fans and service water heating systems, are less than 10% of the total energy use. Only for buildings in Seattle needs 10% of the end use energy for interior lighting. As for space heating, the highest share is observed for Seattle and Buffalo with a demand of 4%, and the least in New York City with 3%. Due to hot climate in Honolulu, no space heating is required. It should be noted here that space heating is fueled by natural gas in the model. Therefore, these patterns also contribute to calculations for emissions profiles.

As for medium office buildings in different climate zones, similar pattern is observed in the share of energy used by different components in the building systems with varied intensity. The highest for receptable equipment is seen for buildings in Seattle with 52%, followed by New York City, Buffalo and Honolulu with 45%, 43% and 40% respectively. Second high share of energy use is found for buildings in Honolulu, 34% for space cooling. In contrast to this finding, Seattle, Buffalo and New York City required relatively lower shares, 6%, 8% and 13% respectively. Compared to the large office buildings, interior lighting systems required more energy in the medium office. The highest in Seattle with 17% followed by New York City, Buffalo and Honolulu with 15%, 14% and 13% respectively. For space heating, highest shares required for medium offices in Buffalo with 23% followed by New York City, Seattle and Honolulu with 15%, 10% and 0%, respectively. Miscellaneous equipment, fans and service water heating systems each required less than 10% of total energy.

In terms of the reported site energy use intensity (EUI) in the large office archetype buildings values range from 156 kWh/m^2 to 192 kWh/m^2. Highest value is observed for buildings in Honolulu and the lowest in Seattle, respectively corresponding to concrete with cavity wall alternative and referenced theoretic model materials used in the envelope structure.

For Honolulu, EUI ranges from 179 to 192 kWh/m^2 where both best and worst values come from concrete cavity wall alternatives. Only variable that impacted this value was WWR, the lowest came from 20% WWR and highest from 90% WWR. Whereas the PNNL reference model resulted in EUI of 185 kWh/m^2.

In New York City, the range is between 163 to 174 kWh/m^2. The lowest value comes from reference model with 20% WWR and the highest comes from concrete with cavity wall alternative with 90% WWR. The reference model with optimized WWR of 40% for buildings in New York City corresponds with an EUI of 165 kWh/m^2. Buffalo city corresponds very closely with New York City. The EUI ranges between 162 to 176 kWh/m^2. These values also correspond identically with building envelope scenarios for buildings in New York City.

Seattle among all the locations have the lowest range of EUI for large office buildings, 156 to 165 kWh/m^2. The best value comes from reference materials with 40% WWR and the worse or highest EUI comes from concrete with cavity wall with 90% WWR.

As for the medium office building, the values ranged between 80 kWh/m^2 and 116 kWh/m^2. Highest value is observed for buildings in Honolulu and the lowest in Seattle corresponding respectively with concrete cavity wall of 70% WWR envelope and reference material with 30% WWR.

EUI results for medium office in Honolulu with varied envelop system ranges between 101 to 116 kWh/m^2. The lowest value comes from reference materials with 15% WWR and the highest from concrete with cavity wall with 70% alternative. The value for reference building model with optimized 30% WWR is 104 kWh/m^2.

In New York City, the values range between 93 to 104 kWh/m^2. The best value come from reference model with optimized 30% WWR and the worst from concrete with cavity wall of 70% WWR.

As for the medium office in Buffalo, values range between 98 to 114 kWh/m^2. Slightly different than the relationship seen in other cities, lowest value comes from reference model with 30% WWR, while the highest comes from cross-laminated timber wall with 70% WWR.

The lowest EUI of all the cities seen in Seattle ranges between 80 to 91 kWh/m^2. The best value is offered by the reference model with 30% WWR while the worst comes from concrete cavity wall alternative with 70% WWR.

4.2. Materials Modeling Results

Results obtained from the materials model for large and medium office building archetypes with changing material composition and WWR are categorized in two groups. Group 1 contains all major materials used for exterior wall (EW) construction and Group 2 consists of all major materials from curtain wall (CW) construction. It should be noted that materials composition does not change with location as the impact is not very significant. Findings from the two types of office buildings with changing WWR and material composition are presented as follows.

The material use intensity (MUI) in the large office building for EW system ranges from 10 to 100 kg/m^2. While for the CW system this ranges between 1 to 47 kg/m^2. Together the MUI for the envelop system ranges between 23 to 105 kg/m^2. In the reference model, MUI ranges from 25 to 98 kg/m^2. The lowest and highest value corresponds with WWR of 90% and 20% respectively. The MUI range for concrete cavity wall alternative lies within 39 to 105 kg/m^2 . Similar to reference model, the WWR has same impact for this alternative. However, different relationship is seen in the cross-laminated timber alternative. The MUI ranges from 23 to 57 kg/m^2, where the lowest and highest corresponds with WWR 40% and 90%, respectively.

As for the medium office building, MUI for the EW system ranges from 11 to 146 kg/m^2 and from 2 to 50 kg/m^2 for CW system. Total MUI in the envelop ranges between 21 to 150 kg/m^2. The lowest and highest values come from envelops with WWR of 70% and 15%, respectively. In terms of materials composition related to the MUI ranges, the reference model has the lowest range within 21 and 26 kg/m^2, while concrete with cavity wall has the highest range from 66 to 150 kg/m^2. MUI in the cross-laminated timber alternative ranges within 41 to 63 kg/m^2. These values also depend on the WWR percentages in the envelop. A similar relationship with the highest and lowest MUI values is seen in the materials alternatives as of the large office buildings. Both reference and concrete with cavity wall envelop MUI decreased increasing WWR except for the timber alternative.

4.3. Emission Results

GHG emissions associated with the energy and material used in the archetype buildings is calculated using the methodology described in Chapter 3.5.3, 3.5.1 and 3.5.2. Results from the calculation is expressed in kg CO_2e/m^2 corresponding to the functional unit of 1 m^2 gross floor area and one year of operation. The findings are presented for large and medium office buildings in terms of highest and lowest emission ranges associated with the location, envelop material composition, and WWR.

Emissions from the large office building translated into global warming potential (GWP) associated with life cycle module A1 – A4 ranges from 23 to 129 kg CO_2e/m^2. In which the largest come from concrete cavity wall (Cs) envelope with 90% WWR in Buffalo, and the smallest come from base (B) envelop in New York City. In terms of medium office buildings, the GWP ranges between 15 to 249 kg CO_2e/m^2. The highest value associate with Cs envelops with 70% WWR in Honolulu. While the lowest from B envelop with 15% WWR in New York City, Seattle and Honolulu. The parameters causing this change is mainly WWR of the envelope, type of material used in the system and manufacturer to building site transport distance.

In terms of GWP from operational energy use at life cycle module B6 in large office building limits between 24 to 135 kg CO_2e/m^2. The highest emissions occur in Honolulu with Cs envelope of 90% WWR, and the lowest for B envelop of 40% WWR in Seattle. The GWP range for medium office lies within 13 to 81 CO_2e/m^2. Highest coming from Cs envelop with 70% WWR in Honolulu. Whereas the lowest come from B envelope with 30% WWR in Seattle.

For the large building archetype, total emissions from the reference model with optimized WWR of 40% ranges from 54 to 160 kg CO_2e/m^2. The lowest and highest values associate with Seattle and Honolulu respectively. The emissions for building in New York City and Buffalo correspond to 59 and 109 kg CO_2e/m^2 respectively. Considering the alternative materials in the envelope, total emission from concrete cavity (Cs) envelop and cross laminated timber (Cl) envelop range between 92 to 197 kg CO_2e/m^2 and 81 to 183 kg CO_2e/m^2 respectively. Among the cities, Honolulu has the highest with 197 and 183 kg CO_2e/m^2 for concrete and timber alternatives respectively. The respective emission profile of 92 and 81 kg CO_2e/m^2 for these two alternatives for large office in Seattle are the lowest among other cities.

The emission profile for large office building also changes with changing WWR. The lowest GHG emission of 50 kg CO_2e/m^2 is seen for 20% WWR in Seattle with reference materials. While the highest 173 kg CO_2e/m^2 is observed in Honolulu for concrete with cavity wall envelope. Similarly, with increased WWR the lowest emission of 67 kg CO_2e/m^2 is seen for Seattle and the highest with 256 kg CO_2e/m^2 in Honolulu for reference materials and concrete with cavity wall, respectively.

In terms of medium office archetype, total emissions from reference model with optimized 30% WWR ranges from 37 to 96 kg CO_2e/m^2. The lowest and highest values associate with Seattle and Honolulu respectively. The emissions for buildings in New York City and Buffalo correspond to 43 and 47 kg CO_2e/m^2 respectively. In terms of the alternative materials related emissions, concrete cavity wall and cross-laminated timber wall range between 159 to 248 kg CO_2e/m^2 and 77 to 132 kg CO_2e/m^2, respectively. Among the cities, Honolulu has the highest with 217 kg CO_2e/m^2 and 132 kg CO_2e/m^2 corresponding to concrete and timber-based envelopes. The respective emission profile of 159 and 77 kg CO_2e/m^2 for these two alternatives are the lowest in Seattle among all other locations.

In relation to the changing WWR in medium office building, the lowest total GHG emission of 30 kg CO_2e/m^2 is seen for 15% WWR in Seattle with reference materials. On the contrary, the highest 254 kg CO_2e/m^2 is emitted from concrete with cavity wall envelope archetype located in Buffalo. Similarly, with increased WWR the lowest emission of 61 kg CO_2e/m^2 is seen for Seattle and the highest with 249 kg CO_2e/m^2 in Honolulu for reference materials and concrete with cavity wall, respectively.

Figure 8 illustrates the relationship between changing WWR and location on EUI and emissions for medium and large office building located using the reference model parameters collected from PNNL repository. Figure 9 and Figure 10 provides a complete overview of impacts from the variables on EUI, MUI and emissions.

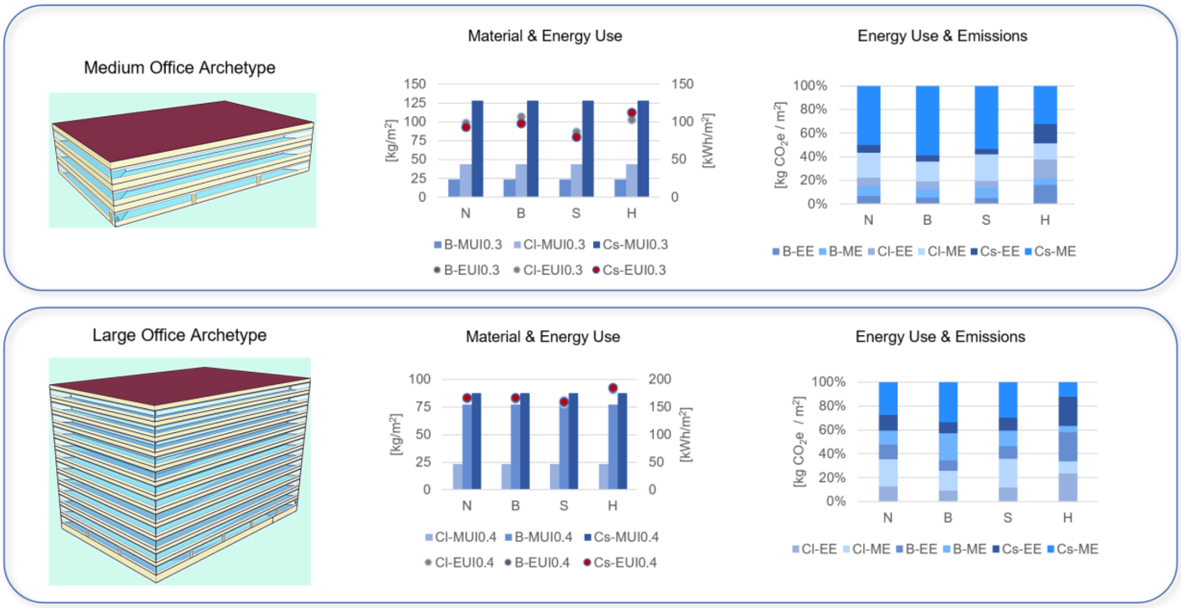


Figure 8 Reference archetype model performance profile

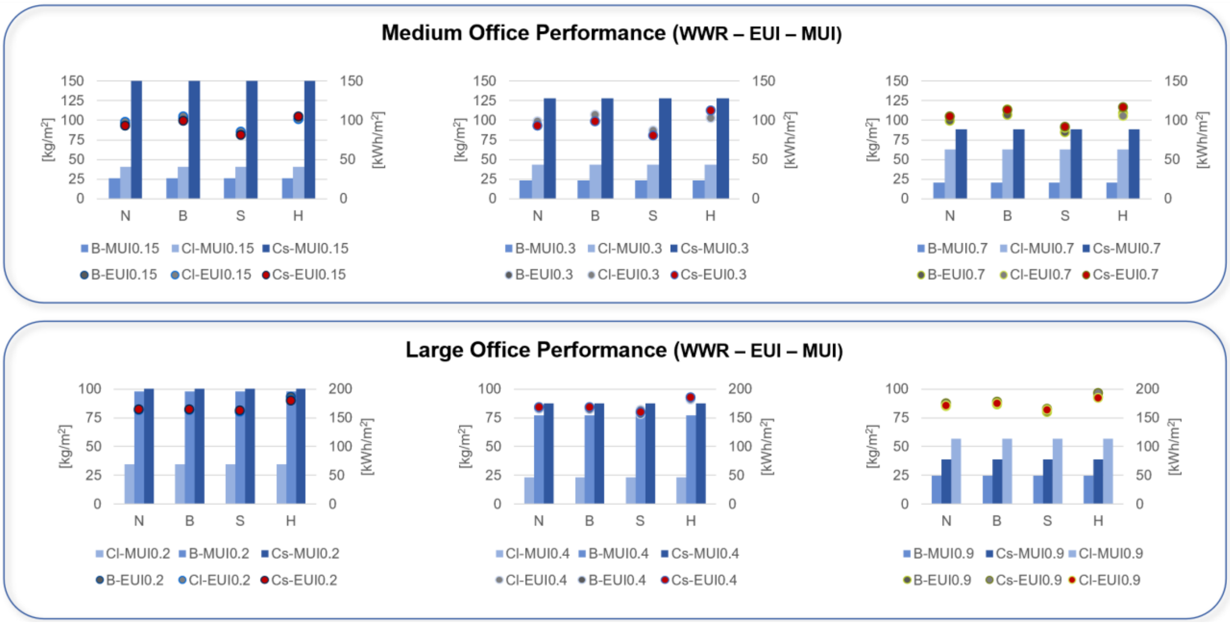


Figure 9 Office building archetype performance related to changing window-to-wall ratio and location

Figure 10 Impact of WWR on EUI and Emissions

4.4. Potential savings from energy standards

The energy saving potential associated with benchmarked values in the studied ASHRAE energy standards version is calculated using a method described in Chapter 3.6, inspired by research done by Athalye and colleagues (2016). Considering the energy benchmarks provided by the 2019 version of ASHRAE 90.1 as the desired EUI performance from office buildings, results obtained from the previous benchmark EUI is calculated to compare electricity saving potential in new construction. Figure 11 provides an overview of gradual improvement in the EUI benchmark values for medium and large office building located in the four study cities.

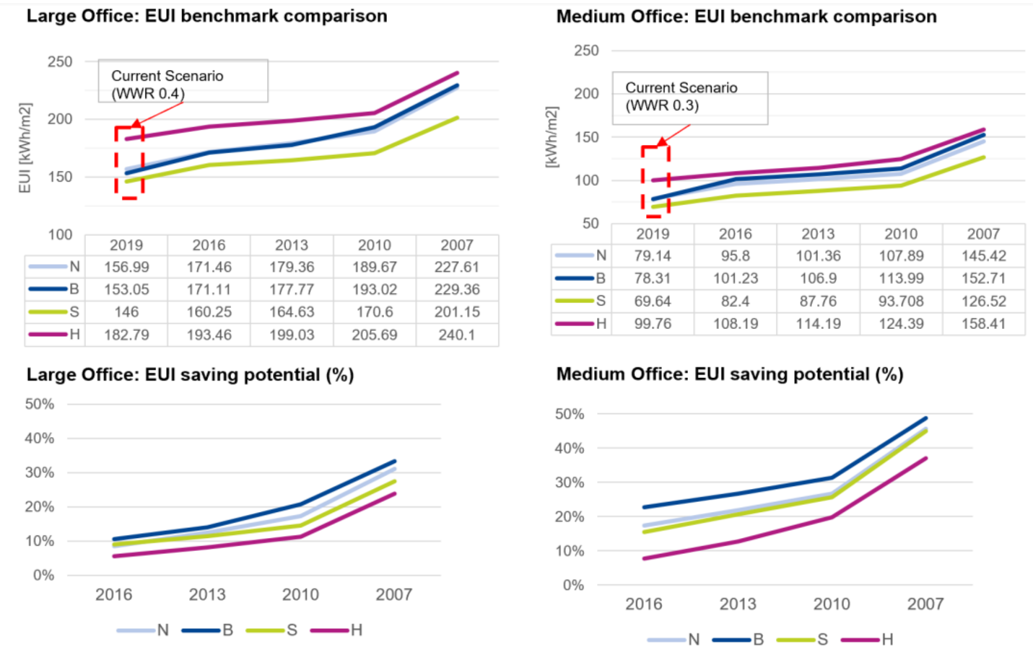
For the large office EUI benchmarked values corresponding to standard version 2007 until 2019 gradually improved from 228 to 157 kWh/m^2, 229 to 153 kWh/m^2, 201 to 146 kWh/m^2, and 240 to 183 kWh/m^2 for New York City, Buffalo, Seattle and Honolulu respectively. From 2007 to 2019, there have been 5 code cycles associated with the 90.1 energy standard. Each of the standard have been revised and updated within 3 years of announcement to the new one. The code cycle to code comparison with the current 2019 benchmark value shows a maximum of 31% and a minimum of 9% saving from large office building in New York City. The maximum saving comes in comparison with 2007 version while the minimum comes from the 2016 version. In Buffalo, Seattle and Honolulu, maximum and minimum saving correspond to 33% and 11%; 27% and 9%; and 24% and 6%, respectively.

For the medium office archetype, EUI benchmark values from standard version 2007 to 2019 gradually improved from 145 to 79 kWh/m^2, 153 to 78 kWh/m^2, 127 to 70 kWh/m^2, and 158 to 100 kWh/m^2, for New York City Buffalo, Seattle and Honolulu respectively. The code cycle to code comparison with the current 2019 benchmark value shows a maximum of 46% and a minimum of 17% saving from large office building in New York City. In Buffalo, Seattle, and Honolulu, maximum and minimum saving corresponds to 49% and 23%; 45% and 16%; and 37% and 8%, respectively.

The method explained in chapter 3.6, is used to estimate yearly electricity use and their associated GHG emission from newly constructed large and medium office buildings in the study cities using benchmark EUI values. The result gives a performance overview of the growing office building stock in these cities. As mentioned earlier, it is assumed that at least 92000 square meters of office floorspace is added yearly in each of these cities. Among this, 20% is large office and 80% is medium office. This results in 18400 square meters of floor area corresponding to large office characteristics and 73600 square meters of floor area corresponding to medium office building model. In reality, this might be overwhelming for small cities like Honolulu or too small for large cities like New York City. For the sake of analysis, as suggested by Athalye et al. (2016), this estimation would provide less error than relying on incomplete dataset. Figure 12 illustrates annual energy and emission savings potential from ASHRAE 90.1 energy standard version 2019.

The large office building stock performance using 2019 benchmark value in the four cities shows, the lowest annual electricity demand and emission from Seattle, corresponding to 9671 GJ and 364 Mg CO_2e. While the highest comes from Honolulu, corresponding to 12108 GJ of electricity demand associated with 2384 Mg CO_2e yearly emission. New York City and Buffalo have similar electricity demand of 10399 and 10138 GJ associated with 496 and 483 Mg CO_2e emissions, respectively. Comparing with the previous benchmark values, the current standard version provides the same percentage of saving potentials for electricity demand and emissions as calculated in the energy version’s EUI benchmark improvement analysis.

Similarly, the medium office building stock performance using the 2019 benchmark value in the four cities shows the lowest annual electricity demand and emission from Seattle, corresponding to 18452 GJ and 695 Mg CO_2e. While the highest comes from Honolulu, corresponding to 26432 GJ of electricity demand associated with 5205 Mg CO_2e yearly emission. New York City and Buffalo have similar electricity demand of 20969 and 20749 GJ associated with 999 and 989 Mg CO_2e emissions, respectively. Saving potentials are consistent with findings from the energy version's EUI benchmark improvement analysis.


Large Office: EUI benchmark comparison

	2019	2016	2013	2010	2007
N	156.99	171.46	179.36	189.67	227.61
B	153.05	171.11	177.77	193.02	229.36
S	146	160.25	164.63	170.6	201.15
H	182.79	193.46	199.03	205.69	240.1

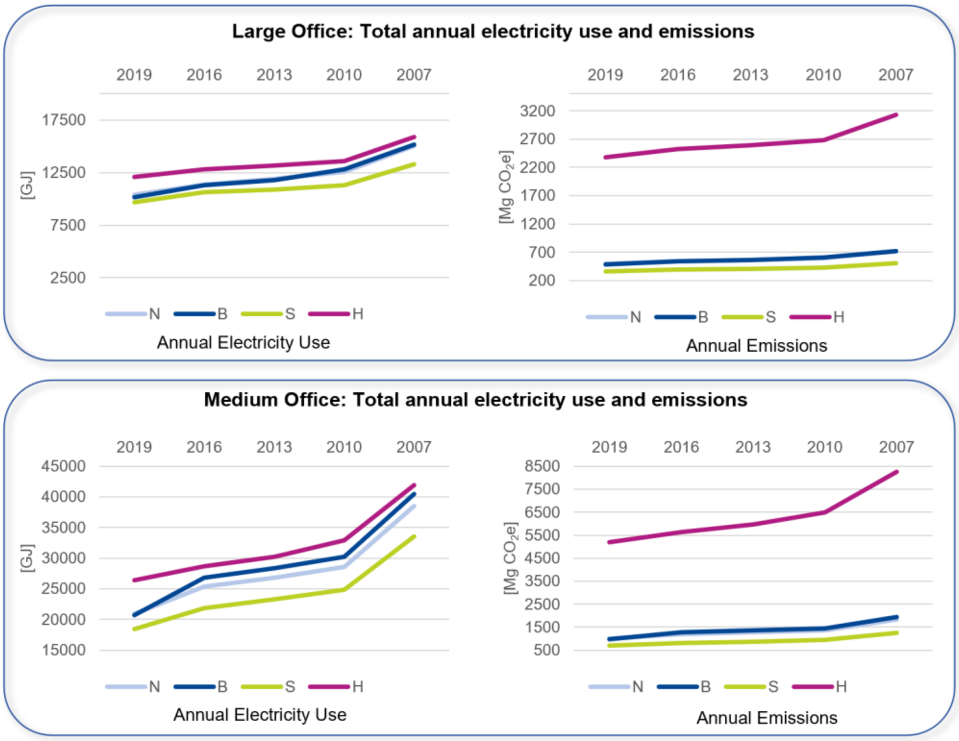
Medium Office: EUI benchmark comparison

	2019	2016	2013	2010	2007
N	79.14	95.8	101.36	107.89	145.42
B	78.31	101.23	106.9	113.99	152.71
S	69.64	82.4	87.76	93.708	126.52
H	99.76	108.19	114.19	124.39	158.41

Large Office: EUI saving potential (%)

Medium Office: EUI saving potential (%)

Figure 11 Impact of energy standard versions on new building stock


Large Office: Total annual electricity use and emissions

Medium Office: Total annual electricity use and emissions

Figure 12 Annual energy and emissions savings from ASHRAE 90.1-2019 energy standard

5. Discussion

This chapter provides a discussion on the results and answers the research questions presented in Chapter 1.1. The findings are also justified with the background study and thoroughly explain unexpected inconsistencies observed in the results. It also criticizes some parts of the research work in terms of limitations and provides a way forward in a suggestive manner for future research.

5.1. Impact of the Parameters

The three key parameters related to location, WWR, and materials associated with the selected building types have different levels of magnitude on energy and material use intensity per floor area. GWP associated with annual operational energy and envelop material changed with the variables.

Dominance of location is observed in the end use energy pattern, energy use intensity and emissions from both energy and materials. It did not have a big impact on the material use intensity per floor area when considered a specific type of building. But a significant effect is observed when calculation GWP in the energy mix and material transportation from the manufacturer's site to the building construction site.

Direct impact from the envelop system, particularly due to WWR change, is seen on material use intensity and its associated GWP. In most cases, the optimized WWR with 30% for medium office and 40% for large office had best performance with less energy demand and emissions. Reduced WWR meant less materials for envelop construction, while increased WWR caused higher material demand associated with higher emissions. Environmentally, WWR has higher impact because material related emissions were much higher in the construction year compared to the emissions from operational energy in the first year. Although the energy related emissions will have dominance over the life cycle of the building as seen in previous researches (Phillips et al., 2020).

In terms of the materials used in the building envelope system, direct impact is observed from exterior wall materials. Compared to the three types of material composition in two categories, concrete wall with steel framed cavity wall (Cs) has shown the highest contribution to energy use, material use and GWP. In terms of the building types, interestingly, medium office buildings required more materials than the large office counterpart.

5.2. Impact of energy standard

The impact of energy standards on commercial buildings performance in the U.S. has already been analyzed in several studies ((Droutsa et al., 2020; Weidong et al., 2020; Athalye et al., 2016; Emmerich & Persily, 2014). The analysis used in this study strongly agrees with similar researches conducted on commercial building prototypes. The ASHRAE 90.1 energy standard version 2019 is expected to have atleast 9% and 17% energy and emissions saving potentials with respect to large and medium office buildings in the study cities. This is true for the most committed states like New York, where the newest energy standards are adopted within a year of publishing the benchmark values.

Similar potentials are expected from Buffalo. For Seattle, if the current locally adapted standard follows the benchmark EUI values from ASHRAE 90.1 version 2019, then new office buildings would have the same performance as analyzed in the study. According to the analysis done by Athalye and colleagues (2016), the savings potential in Honolulu would be much higher than the other three cities, as the state of Hawaii has not adopted any of the energy standards proposed by ASHRAE 90.1.

The calculations were done using benchmarked EUI values in the four cities and their associated GWP provides an idea about the office building stock that has been added annually in those respective years. For example, if the assumed amount of large and medium office space were constructed in New York City in the year 2017 following ASHRAE 90.1-2016 energy standards, they would need 36741 GJ of energy which would emit about 1751 Mg CO_2e. Considering consistent growth in the floor area in New York City in 2021, using ASHRAE 90.1-2019 standard, the energy demand would be 31368 GJ causing total emission of 1495 Mg CO_2e. This means the new stock require 5373 GJ less energy to operate that results in 256 Mg CO_2e less emissions. Hence, the newest standard brings opportunity to reduce both energy demand and environmental impacts embeded in the building stock.

However, the energy standard adoption monitored by the Building Energy Codes Programe (BECP) only considers state level commitments and does not reflect on the city level activities. Therefore, the assumptions used in these study may not reflect on the actual pace of standards implementation for buildings being constructed in the individual cities.

Apart from the direct EUI specific impact, the standards also implement stringent requirement on the materials to be used in a building. This has been the driving factor of the energy modules that distinguished building's performance in each of the modeled scenarios. The energy standard requirements impose limits for variables in the building components to meet the benchmarked performance. Such variables consist of the materials' thermal properties, building's form and orientation, allowable window opening area, window-to-wall ratio, equipment type, operational schedule with HVAC optimization factor, etc.(Kneifel et al., 2019; Winiarski et al., 2014).

Benchmarked performance values specific to the thermal properties in the envelop components encourage designers and engineers to improve the quality of the envelope system. For example, the optimal thermal values provided for exterior wall and window components showed the best performance in most of the scenarios studied in this research. This has a direct impact on the EUI benchmarks in each of the energy standard versions because the thermal conductance or U-values for envelope components were optimized in every version of the ASHRAE 90.1 standard (Winiarski et al., 2018). The two alternatives envelop systems modeled in the study directly translates this impact of standards for materials interventions.

The modeled alternatives used a generic thermal conductance specific to the materials used in the system. They possessed a threshold value that could not be overestimated to meet the threshold given in the theoretic components proposed in the reference model. The impact of this is in different cities is clearly seen in the summary results visualized in Figure 8 the best and the closest to the theoretical material imposed EUI performance could be achieved by the CLT alternative (represented as Cl in the figures) and the worse Cs alternative provided better performance than referenced materials and Cl. One of the major factors that manipulates the building's energy performance in this aspect is the thermal property of the material used in the envelop. Therefore, to improve the thermal performance of the envelop, engineering interventions is required to develop materials to construct the exterior wall and window components.

5.3. Impact of envelop material

Comparing the results in Figure 9 presented in previous chapter 5.3, direct impact of exterior wall materials is observed in each of the archetype scenarios. While the EUI remained within a very close range in each of the study city, MUI and GWP values fluctuated in a significant manner. Also, comparing the two types of the buildings, medium office building requires a higher amount of material per floor area than large office building. This was due to the construction type of the exterior wall system that triggered such results.

When considering the impact from the curtain wall on envelope, the WWR changed MUI requirement on the system. Reduced WWR demanded less material for the curtain wall glazing component while increasing demand on opaque wall materials. The opposite happens with increased WWR. An interesting finding here is that the wooden frame curtain wall on Cl alternative demanded higher MUI compared to the other two alternatives. This is because wood frames are heavier than aluminum frames. The results also agree with the findings observed in previous studies (Tywoniak et al., 2014) (Azari-N & Kim, 2012).

Environmental performance of the archetype buildings with changing envelop systems contributed to at least 50% of the total GWP. While the best GWP is observed for theoretic materials from B envelop systems in both medium and large office buildings, the worst is observed from the Cs envelop systems.

This is because Cs envelop contains concrete with steel and curtain wall with aluminum frame. Both materials have higher carbon content as opposed to the reference B envelop construction.

The CLT alternative was expected to have the best environmental performance as presented by Pierobon and colleagues findings (Pierobon et al., 2019). But due to the increased MUI and comparative low energy efficiency of the system, this alternative did not show the best results. Also due to the defined scope of LCA stage in this study, the long-term benefits of CLT system is not visualized in the results presented in this research.

5.4. Limitations

The results indicate to some of the limitations of this study which are identified and explained briefly in this sub-chapter.

One of the shortcomings of the analysis in this thesis is that it considers a fixed value to model the infiltration rate on the envelope. This issue has been noticed by the PNNL researchers as well. The reason behind setting a fixed value was to minimize over assumption and under assumption impact magnitude which is a validated reason. The infiltration through a changed envelop system, such as the CLT alternative, may have a significance with regards to the thermal performance of the new system. An additional variable associated to the infiltration values is believed to improve the quality of this analysis for the alternative materials scenarios.

The curtain wall system modeled in this study uses the simple input parameters in the EnergyPlus software. The limitations of this approach are that the curtain wall components are simplified as fenestration surfaces and the materials are modeled using thermal properties of the material. It is an effective and time-efficient method for energy specific studies, but with limitations considering the engineering details. For example, the sealers and spacers used between curtain wall mullion and glass ensure performance of the component (Aksamija & Peters, 2017). This was not modelled in detail to test the variables impact on energy use. It can be considered as scope to improve the modeling of envelop system.

The approach to model alternative envelops system consisted of using materials and components library from BCL developed by the U.S. National Renewable Energy Laboratory (NREL). Although the contents were suitable for building energy models aligned with the research scope, it didn’t contain enough alternatives with advanced materials. Therefore, it was difficult to model an alternative curtain wall system that had the same level of ambition required by the ASHRAE 90.1-2019 energy standard. The analysis would have better results if more information on thermally improved envelop components were accessible.

In terms of analyzing the stock specific performance in relation to the energy standard version, generic assumption on city specific growth is used. This is because the low sample data available from CBECS and missing city specific information. To improve data quality for the new building stock analysis, it would require field data collection from each of the cities which would have been both time consuming and inaccessible. As an alternative, suitability of building performance database (BPD) was analyzed at the initial phase of the research (BPD, n.d.). Although the datasets had some level of representation of commercial building stock characteristics at a national scale, but missed sampling accuracy for office buildings (Walter & Mathew, 2019). Therefore, a thorough sampling of new building stocks in each survey region and cities is necessary for better understanding of energy performance in buildings.

In terms of environmental impact assessment using a ready-made LCIA database, the characterization factor for some processes have been generalized to regional scale. This may cause over estimation for one city and under estimation for others. This was also hard to estimate GWP for curtainwall systems, because the ecoinvent database did not include curtainwall as a product and EPD from manufacturers did not provide assessment for all materials used in the system. Therefore, a logical calculation had to be conducted consulting reference flows in the curtain wall EPDs and separate window and frame specific processes from ecoinvent database. A complete LCA on each envelop system would improve the quality of the results obtain in this research. That approach would require much more time with undermining the quality of available LCI for advanced envelop systems.

5.5. Future Research

The limitations addressed in previous sub-chapter can be noticed in further research. As a progression of this work, an integrated building modeling method can be developed that uses major component specific parameters and performs a complete life cycle analysis including materials, operational energy use and compliance with ASHRAE 90.1 energy standards. The Athena IE4B, in this aspect had all these qualities, but it required more effort to match the buildings model that resembles the PNNL commercial prototypes. A new method incorporating existing tools and databases may provide wider scope of analysis and better quality of result.

Furthermore, to analyze performance of the growing office building stock in the U.S. cities, through groundwork is required. This can be done in collaboration with research groups with similar interests which can result in an open access database for buildings.

Another aspect of this research is that it examines the saving potentials of energy standards and relates with the practicality of their implementation in a simplified manner. There are several underlying issues in relation to a city's commitment and capacity to implement the rigid EUI benchmarks for commercial buildings. Such perspectives can be assessed using a socio-environmental hybrid life cycle model to justify the practical implementation of energy standards in cities.

6. Conclusions

The goal and scope of this study were to analyze the effects of the most recent energy standard on energy and materials use intensity associated with GHG emissions from building envelope in the U.S. office buildings. Reviews on the existing research showed multiple approach to the topic separately in a broader scale but lacked an overall assessment of a particular component such as the envelop. The assessment scope of this study provides an opportunity to understand a buildings energy and environmental performance in relation to standards driven thresholds values. It unravels the relationship between the most influential parameters such as location, geometry and material as well as a way to analyze energy demand and emissions reduction potential in freshly built stock.

The investigation utilized detailed energy models of two types of office buildings located in four cities with distinctive climatic characteristics. The modeled office buildings resemble majority of the exiting office building stock in the U.S. It also selected a set of variables that are most influential for energy performance in buildings and set parameters to match the requirement from chosen energy standard version being studied. The work initiated by setting archetypes for medium and large office buildings and creating about 36 archetypes in total by manipulating the parameters belonging to the selected variables. A set of databases provided by the U.S. DOE supported initiative for building energy codes program were considered as the basis to form the archetype models. These models were used as inputs for energy simulations which in later stage provided annual energy use characteristics of the building. To quantify materials used in the envelope, a python script was modified to consider the archetype parameters from the energy model and extract information normalized the functional unit as defined in this study. The final energy and material use intensity were expressed in terms of kWh/m^2 and kg/m^2, respectively. It should be noted that the comparisons are done for 1 m^2 of gross floor area and year which for energy use translates as one year of operation. In terms of materials use it would mean one year of service life.

In terms of the reported site energy use intensity (EUI) in the large office archetype buildings values range from 156 kWh/m^2 to 192 kWh/m^2. Highest value is observed for buildings in Honolulu and the lowest in Seattle respectively corresponding to concrete with cavity envelop alternative and referenced theoretic materials used in the envelope structure. The material use intensity (MUI) for the envelop system in the large office building ranges between 23 to 105 kg/m^2. The lowest and highest value corresponds with WWR of 90% and 20% respectively. Although a different relation is observed for the cross-laminated timber alternative where the lowest and highest MUI corresponds with WWR 40% and 90% respectively. Total emissions from the reference model with optimized WWR of 40% ranges from 54 to 160 kg CO_2e/m^2. The lowest and highest values associate with Seattle and Honolulu respectively. The lowest GHG emission of 50 kg CO_2e/m^2 is seen for 20% WWR in Seattle with reference materials. While the highest 173 kg CO_2e/m^2 is observed in Honolulu for concrete with cavity wall envelope. Similarly, with increased WWR the lowest emission of 67 kg CO_2e/m^2 is seen for Seattle and the highest with 256 kg CO_2e/m^2 in Honolulu for reference materials and concrete with cavity wall, respectively.

As for the medium office building, the values ranged between 80 kWh/m^2 and 116 kWh/m^2. Highest value is observed for buildings in Honolulu and the lowest in Seattle corresponding respectively with concrete cavity wall of 70% WWR envelope and reference material with 30% WWR. Overall, MUI in the envelop ranges between 21 to 150 kg/m^2. The lowest and highest values come from envelops with WWR of 70% and 15% respectively. A similar relationship with the highest and lowest MUI values is seen in the materials alternatives as of the large office buildings. Both reference and concrete with cavity wall envelop MUI decreased increasing WWR except for the timber alternative. In terms of medium office archetype, total emissions from reference model with optimized 30% WWR ranges from 37 to 96 kg CO_2e/m^2. The lowest and highest values associate with Seattle and Honolulu, respectively. The lowest total GHG emission of 30 kg CO_2e/m^2 is seen for 15% WWR in Seattle with reference materials. On the contrary, the highest 254 kg CO_2e/m^2 is emitted from concrete with cavity wall envelope archetype located in Buffalo. Similarly, with increased WWR the lowest emission of 61 kg CO_2e/m^2 is seen for Seattle and the highest with 249 kg CO_2e/m^2 in Honolulu for reference materials and concrete with cavity wall, respectively.

The dominance of location is observed in the end use energy pattern, energy use intensity and emissions from both energy and materials. It did not have a big impact on the material use intensity per floor area when considered a specific type of building. Direct impact from the envelop system, particularly due to WWR change is seen on material use intensity and its associated GWP. In most cases, the optimized WWR with 30% for medium office and 40% for large office had best performance with less energy demand and emissions. In terms of the materials used in the building envelop system, direct impact is observed from exterior wall materials. Compared to the three types of material composition in two categories, concrete wall with steel framed cavity wall (Cs) has shown highest contribution to energy use, material use and GWP. In terms of the building types, interestingly, medium office building required more materials than the large office counterpart.

Considering the energy benchmarks provided by the 2019 version of ASHRAE 90.1 as the desired EUI performance from office buildings, results obtained from the previous benchmark EUI is calculated to compare electricity saving potential in new construction. The code cycle to code comparison with the current 2019 benchmark value shows a maximum of 46% and a minimum of 17% saving from large office building in New York City. In Buffalo, Seattle and Honolulu, maximum and minimum saving correspond to 49% and 23%; 45% and 16%; and 37% and 8%, respectively.

The large office building stock performance using the 2019 benchmark value in the four cities shows, the lowest annual electricity demand and emission from Seattle, corresponding to 9671 GJ and 364 Mg CO_2e. While the highest comes from Honolulu, corresponding to 12108 GJ of electricity demand associated with 2384 Mg CO_2e yearly emission. Similarly, for medium office building stock the lowest annual electricity demand and emission from Seattle, corresponding to 18452 GJ and 695 Mg CO_2e. While the highest comes from Honolulu, corresponding to 26432 GJ of electricity demand associated with 5205 Mg CO_2e yearly emission.

These results show the ambition of ASHRAE 90.1-2019 energy standards for the newest office building stocks in the U.S. The expect performance and shift in the performance characteristics highly depend on implementation of the standards into practice. Furthermore, electricity mix in the national grid and types of materials selected in the envelop will also govern how efficient the building will be in terms of energy and environmental footprint. A fossil free energy mix and biobased material will contribute to significantly low GWP while the opposite is expected from the fossil based and carbon intensive conventional building material.

Thorough analysis such as this research paves ways to further exploration and conversation on building performance improvement potentials. It sheds light on the issues like necessity to develop light yet thermally effective materials to reduce material and energy demand in buildings. It also calls for a multi-disciplinary approach to solve design and construction related impacts at the initial phase of building. Furthermore, the analysis can be used to develop a strategy to increase efficiency in the existing building stock while preparing for the once under making.

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Appendices

Appendix 1 City specific climate Data

City, State	Climate Region	Weather File
New York City, NY	4A – mixed, humid	New.York-J.F.Kennedy-Intl.AP.744860_TMY3
Buffalo, NY	5A – cool, humid	Buffalo-Greater.Buffalo.Intl.AP.725280_TMY3
Seattle, WA	4C – mixed, marine	Seattle-Tacoma.Intl.AP.727930_TMY3
Honolulu, HI	1A – veryhot, humid	Honolulu.Intl.AP.911820_TMY3

Appendix 2 Thermal Property of Construction Material

Description	Reference – Large Office	Reference – Medium Office	Alternative 1	Alternative 2
Wall construction	Pre-cast Concrete Wall	Steel Frame Stucco Wall	Concrete with steel frame (CSF)	Cross Laminated Timber (CLT)
U-value* [W/m2-K] per City				
New York City	0.591	0.363	0.341	0.285
Buffalo	0.511	0.312	0.341	0.285
Seattle	0.591	0.363	0.341	0.285
Honolulu	2.882	0.704	0.341	0.285

*U-values represent the opaque exterior wall construction U-factor with factor to reflect the panel impact and not only a single material's thermal property.

Appendix 3 Thermal Property of Glazing Material

City	New York City	Buffalo	Seattle	Honolulu
Simple Glazing (U-Value [W/m2-K], SHGC)	2.045, 0.355	2.045, 0.374	2.045, 0.355	2.843, 0.232
Low-E double glazed (U-Value [W/m2-K], SHGC)	1.779, 0.493	1.779, 0.493	1.779, 0.493	1.779, 0.493
Aluminum Frame (U-Value [W/m2-K])	0.17	0.17	0.17	0.17
Reflecsive double glazed (U-Value [W/m2-K], SHGC)	2.01, 0.132	2.01, 0.132	2.01, 0.132	2.01, 0.132
Wood Frame (U-Value [W/m2-K])	0.28	0.28	0.28	0.28
Exterior Door (U-Value [W/m2-K])	1.598	1.598	1.598	1.598

Appendix 4 Materials Inventory: Large office

Model/Material	**Archetype Material Intensity [Kg/m2]**		
	Reference Archetype		
	WWR0.4	WWR0.2	WWR0.9
Concrete	65.55	87.20	10.80
XPS insulation	0.01	0.02	0.00
Gypsum board	8.82	9.29	7.64
Simple double paned window	2.79	1.41	6.27
	CSF Archetype		
Concrete	65.55	87.20	10.80
Steel framed cavity insulation3	3.26	4.34	0.54
Gypsum board	8.82	9.29	7.64
Double paned window with low-e glass	2.79	1.41	6.27
Aluminum window frame[1]	5.58	2.82	12.54
	CLT Archetype		
Wood fiberboard	0.39	0.52	0.06
Wood fibrebatt	0.56	0.74	0.09
OSB vapor retarder	10.67	14.19	1.76
Gypsum board	8.79	9.25	7.64
Double paned window with reflexive and clear glass	2.79	1.41	6.27
Wooden window frame[2]	16.73	8.47	37.62

[1] Aluminum frame is assumed to be 4 times heavier than glass. (ABNT, 2005)

[2] Wooden frame is assumed to be at least 1.5 times heavier than aluminum frame. (Ecoinvent, 2020; Tywoniak et al., 2014)

Appendix 5 Materials Inventory: Medium office

Model/Material	**Archetype Material Intensity [Kg/m^2]**		
	Reference Archetype		
	WWR0.3	WWR0.15	WWR0.7
Stucco	10.66	13.18	4.21
XPS insulation	0.02	0.03	0.01
Gypsum board	10.11	11.48	6.63
Simple double paned window	3.11	1.50	7.21
	CSF Archetype		
Concrete	106.65	131.92	42.09
Steel framed cavity insulation	5.31	6.57	2.10
Gypsum board	6.66	7.20	5.27
Double paned window with low-e glass	3.11	1.50	7.21
Aluminum window frame[1]	9.32	4.50	21.63
	CLT Archetype		
Wood fiberboard	0.64	0.79	0.25
Wood fibrebatt	0.90	1.12	0.36
OSB vapour retarder	17.36	21.47	6.85
Gypsum board	6.62	7.15	5.25
Double paned window with reflexive and clear glass	3.11	1.50	7.21
Wooden window frame[2]	18.63	8.99	43.26

[1] same as assumed for LO archetypes. [2] same as assumed for LO archetypes.

Appendix 6 Additional materials information for calculation

Materials	**Density**[1]	**Thickness**[1]
Glass: Clear 6mm, Low-e Clear 6mm, Ref A Clear Lo 6mm	2500	0.006
Glass: Low-e Clear 3mm	2500	0.003
Glazing Layer	2500	0.006
Glazing	2000	0.006
Nonres_Exterior_Wall_Insulation	20.8	0.005
Argon 13mm	1.7837	0.013
Opaque door panel_con	1762	0.045
Frame with Cavity Insulation	235	0.1

[1] Information collected from generic engineering materials specification list (Windsor-csd, n.d.)

Appendix 7 Materials excluded in the calculation

Name	**Surface Information**	**Comment**
Air 6 mm	Fenestration	No impact on energy or environment
CP02 Carpet Pad	Building Surface: Floor slab	Out of research scope
Semiheated_Floor_Insulation	Building Surface: Floor	
Nonres_Roof_Insulation	Building Surface: Roof	
Semiheated_Roof_Insulation	Building Surface: Roof	

Appendix 8 LCIA datasets for materials and transport emissions

Material	**Process**[1]	**Normalized**[2] **GWP100 [Kg CO_2e/m^2]**
Concrete	Market for concrete, 25MPA, North America without Quebec	0.091
Stucco	Market for stucco, GLO	0.095
Polysterene (XPS)[3]	Polysterene production (XPS), extruded, HFC-134a blown, CA-QC	24.39
Gypsum	Market for gypsum fibreboard, GLO	0.28
Fibreboard	Fibreboard production, soft, from wet & dry processes, CA-QC	0.025
Ecobatt-Knauf insulation[3]	Knauf Manufacturer data, US	1.99
Oriented strand board (OSB)	Oriented strand board production (OSB), RER	0.02
Glazing	Market for glazing, double, U<1.1 W/m2K, laminated, GLO	1.90
Aluminium frame	Market for window frame, aluminium, U=1.6 W/m2K, GLO	13.17
Wooden frame	Market for window frame, wood, U=1.5 W/m2K, GLO	2.21
Curtain wall with aluminium mullion[4]	Combined with double glazed window and aluminium frame	6.15
Curtain wall with wood mullion[4]	Combined with double glazed window and wooden frame	2.61
Materials Transport	Market group for transport, freight, lorry, unspecified	0.000133 [Kg CO_2e/ Kg * km]
Ready-mix Concrete Transport	Ready-mix concrete truck, 1830.84 kg capacity	0.0012 [Kg CO_2/ Kg*km][5]

[1] Most of the process specific datasets come from Ecoinvent 3.7.1, cut-off allocation, ReCiPe midpoint method.

[2] Normalized GWP100 values indicates that the collected process values are converted into the functional unit used in this study.

[3] Data for leading polystyrene XPS producers in Germany and USA; EPD data from Knauf insulation.

[4] Calculations for the curtain wall life cycle impact required modification for functional unit and window system.

[5] Methods adopted from Palaniappan and Stecker (2009) and normalized to functional unit for emission modeling.

Appendix 9 LCIA datasets for electricity

City	Region (State, Country)	Normalized[1] GWP100 [Kg CO_2e/kWh]
Buffalo	New York, US	0.17
Honolulu	Hawaii, US	0.71
New York City	New York, US	0.17
Seattle	Washington, US	0.14
Natural Gas	Average in US	0.405 [Kg CO_2e/ KWh][2]

[1] Normalized GWP100 values mean that the collected state specific values were converted into the units relevant for this study. It should also be mentioned that the emissions calculations for electricity related impacts followed IPCC emissions reporting format.

[2] Normalization factors using USDOE unti conversion tools. GWP100 values follow IPCC 2007 calculation method.

NTNU

Norwegian University of
Science and Technology