EVALUATING THE IMPACT OF OPERATING ENERGY REDUCTION MEASURES ON EMBODIED ENERGY

A Thesis

by

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ABSTRACT

Buildings are known to consume around 48% of the world's annual energy in their construction, operation and maintenance causing significant damage to the environment due to the resultant carbon emissions. During their lifecycle, buildings consume energy in the form of embodied energy (EE) and operating energy (OE). In a conventional building, EE accounts for 10-20% of a buildings lifecycle energy (LCE), while OE accounts for 80-90%. As a result, the building sector has taken several measures to reduce OE consumption in buildings. These OE reducing measures fail to account for the subsequent increase in EE, and might result in increasing the overall building's LCE. A systematic review of literature shows that, there is limited research that comprehensively evaluates the impact of OE reduction measures on EE for different construction assemblies. Therefore, making the design decision process extremely tedious and complex. This study has created a knowledge base that would inform energy optimization decision-making during the building's lifecycle. For this, LCE consumption is calculated and evaluated on ASHRAE's 90.1-2016, benchmark model for each OE reducing measure across different commercial building envelope construction assemblies. In future, this knowledge will allow building designers to take an informed step towards reducing overall energy consumption in buildings.

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NOMENCLATURE

EE	Embodied Energy
OE	Operating Energy
LCE	Lifecycle Energy
LCEA	Lifecycle Energy Analysis
BIM	Building Information Modelling
IEE	Initial Embodied Energy
REE	Recurrent Embodied Energy
DE	Demolition Energy
GBS	Green Building Studio
O and M	Operation and Maintenance
EUI	Energy Use Intensity
WWR	Window to Wall ratio

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1. INTRODUCTION

Today’s world is facing several environmental concerns such as climate change, ozone layer depletion, energy crisis, global warming, waste accumulation, rapid urbanization etc., (Lim et al., 2018; Cabeza et al., 2014). Current research shows that the building industry consumes around 48% of the world’s energy annually, making it a major contributor of greenhouse emissions (Dixit, 2017). This is because buildings consume energy during their entire lifecycle i.e. construction, operation, maintenance, renovation and demolition (Dixit, 2017; Cabeza et al., 2014; Ibn-Mohammed et al., 2013). The increase in global energy consumption, emphasizes upon the need to improve the energy-efficiency of a building to meet the required demand (Bakar et al., 2015). As a result, several studies have looked into active and passive measures to achieve energy-efficient building designs (Lim et al., 2018). In addition, multiple building energy assessment tools have been developed over the last few years to inform designers regarding the energy consumption of a building and optimize their designs (Hernandez and Kenny, 2011). These tools generate several design options and evaluate them based on their energy consumption (Wang et al., 2005). With these tools generating several design options, and the involvement of multiple design variables - the design decision making process for an energy-efficient building becomes an extremely complex process (Lim et al., 2018).

Most recently, the building industry has shifted its focus towards net-zero energy buildings (NZEB), carbon neutral buildings, and even net-positive buildings (Lutzkendorf et al., 2014). Although, these high-performance buildings consume minimal energy for their operation they are associated with high embodied energy (EE) consumption (Hernandez and Kenny, 2011; Ramesh et al., 2010). This is due to the fact that these buildings often employ additional material, technology or systems to decrease the energy demand during their use-phase (Lim et al., 2018; Cabeza et al., 2014; Hernandez and Kenny, 2011). Therefore, making it particularly critical to assess embodied energy (EE) impacts as we approach NZEB or carbon neutral buildings. However, literature shows that numerous studies fail to assess building energy from a lifecycle perspective. Generally, these studies tend to concentrate upon reducing the OE consumption of a building (Zuo et al., 2017). Moreover, most of these building energy assessment tools are extremely disjointed, making it difficult to simultaneously assess operating energy (OE) and embodied energy (EE) requirements in a building (Lim et al., 2018). As a result, designers do not have sufficient information regarding building lifecycle energy evaluation methods or the practical guidance to perform holistic lifecycle energy analysis (Lutzkendorf et al., 2014). Nevertheless, to achieve overall reduction in building energy, it is important to reduce both operating and embodied energy.

In this study, we have created a comprehensive knowledge base that evaluates the EE implications by various OE reduction strategies for different building envelope construction assemblies. The study is focused upon comparing OE and EE results for various design options in two different climate zones (heating dominated and cooling dominated) for a building lifespan of 60 years. The findings from this study provides useful information regarding building energy trade-offs that would help building design decision makers identify appropriate energy conservation measures from a building lifecycle perspective. Furthermore, this study can be extended to evaluate other sustainability indicators such as global warming potential, acidification potential, eutrophication potential, human toxicity etc. In the future, this study would help in developing tools and technologies that evaluate building energy trade-offs thereby enabling overall lifecycle energy reduction.

2. LITERATURE REVIEW

2.1. Understanding building lifecycle energy and its components

The building's life cycle energy (LCE) consists of the following components: embodied energy (EE), and operating energy (OE) (Cabeza et al., 2014). Building lifecycle energy assessment (LCEA) is the process of quantifying and evaluating the energy flows in a building system (Ramesh et al., 2010). LCEA, helps in evaluating the environmental performance of the various products and processes used in construction over their entire lifecycle. This includes extracting the raw material, manufacturing the products, transporting these products on-site, using, disposing and recycling them. Therefore, the LCEA is also considered as a "cradle to grave" approach of evaluating environmental impacts (Cabeza et al., 2014). The application of LCEA, has gained significant popularity over the last two decades, due to its holistic approach of evaluating building energy at more than one lifecycle phase and also acknowledging interactions between different lifecycle phases (Zuo et al., 2017).

2.1.1. Embodied energy (EE)

The EE of a building includes the sum of the energy embodied in the building material (extraction, manufacturing and transportation) and the building construction energy (Dixit, 2017; Copiello, 2016; Shrivastava and Chini, 2012). According to Dixit (2017) the EE of a building consists of three major components: initial embodied energy (IEE), recurrent embodied energy (REE), and demolition energy (DE). The IEE will include the sum of all the direct (e.g. construction and transportation) and indirect (mining, transporting and transforming construction material) energy requirements related to the construction of the building (Dixit, 2017; Copiello, 2016). Energy embodied in building materials constitute a major portion of EE in buildings (Praseeda et al., 2016). Therefore, appropriate material selection plays a crucial role in reducing EE of buildings. Using materials with high EE such as brick, glass, cement aluminum, steel etc., results in increasing the EE of a building (Praseeda et al., 2016). The REE includes the energy required to replace or refurbish certain materials that are used in the building since the lifetime of the material is lesser than the building's service life (Ramesh et al., 2010). The REE expenditure mostly occurs during the operations and maintenance (O and M) phase of a building's lifecycle (Dixit, 2017). The DE, is the energy consumed during the end of a building's service life to demolish and dispose the various building components (Dixit, 2017; Ramesh et al., 2010).

2.1.2. Operating energy (OE)

The OE refers to the energy spent on operating and maintaining (O and M) the building. This includes heating, ventilation and air-conditioning (HVAC) loads, lighting loads and plug loads (Karimpour et al., 2014; Sartori et al., 2012; Thormark, 2002). The components of space conditioning and lighting requirements are predominantly dependent upon the location of the building (climate zone), and the occupant's comfort. Generally, building located in extreme climatic zones, consume higher OE to meet their heating and cooling requirements (Praseeda et al., 2016). Several studies show that a more than half of the building’s LCE is consumed during O and M phase in the form of OE (80-90%). This is followed by the embodied energy (10-20%), while the demolition energy has a negligible share (Zeng and Chini, 2017; Chastas et al., 2016; Karimpour et al., 2013; Ramesh et al., 2010).

Since OE consumes most of the building’s energy, lot of attention has been given to this aspect of building design to decrease OE demand. This need to reduce the OE demand in buildings, has led to the use of energy-intensive material (in terms of their production process) (Copiello, 2016). For example, a study conducted by Lu et al. (2015) increased the insulation thickness of the exterior walls to reduce OE consumption. However, there was no discussion regarding the subsequent increase in EE. This issue becomes significant as we approach energy efficient buildings, carbon-neutral buildings or net-zero energy buildings (NZEB).

2.1.3. Net-zero energy buildings (NZEB)

The concept of a NZEB, is based upon an innovative approach to mitigate OE consumption in a building (Praseeda et al., 2016; Kapsalaki et al., 2012). A NZEB, needs to maintain a zero-energy balance annually. To elaborate further, NZEB’s produce energy onsite using renewable sources of energy such as photovoltaic panels. These panels produce energy that is required for the building operation and its occupants over a one-year period (Lutzkendorf et al., 2014). In certain scenarios, there is a need for NZEB’s to borrow energy from the electric grid. However, they are equipped with systems that generate energy which can then be exported into the electric grid to ensure that the annual energy-balance is zero (Kapsalaki et al., 2012). An energy efficient building, regulates and controls the amount of energy consumed while maintaining a thermally comfortable ambience for its occupants (Bakar et al., 2015). To minimize their energy needs, these buildings use several energy-efficient measures that adopt new technology and renewable sources of energy (Bakar et al., 2015. Very often these energy efficient measures significantly increase EE, sometimes even contributing towards nearly 98% of the total building energy. Upon comparing the building LCE between NZEB and conventional buildings, the LCE consumption in NZEB are higher due to the increased EE demand.

2.2. The building envelope and its components

The indoor and outdoor environments are separated by the building envelope. The thermal performance of the building envelope is a crucial factor that controls the quality of the indoor ambient conditions and ensures occupant comfort. The building envelope consists of several components such as – walls, fenestrations (windows and doors), roofs, foundations, thermal insulation, thermal mass, shading devices etc., (Sadineni et al., 2011). A building's thermal envelope can be designed in a number of ways to reduce operating energy (Gustavsson et al., 2010).

2.2.1. Heat gain through the building envelope

The study conducted by Pacheco et al. (2012), shows that the thermal performance of a building envelope, influences nearly 75% of a building's OE loads. Generally, heat gain in building envelopes occur due to conduction, convection and radiation (Lam et al., 2005). In a building envelope, conduction occurs through the opaque envelope assemblies (U-value), convection occurs due to natural or pressure-driven air movements and radiation occurs due to solar heat gain from openings (Lam et al., 2005). Building envelopes have varying requirements based on the needs of a specific geographical location (Li et al., 2013). Generally, limiting the amount of summer heat gain and winter heat loss through the building envelope improves its thermal performance (Li et al., 2016). The key factors that influence the thermal performance of a building envelope are orientation, exterior wall area and construction type (thermal insulation and U-value), surface finish, glazing type and size of windows (wall to window ratio), exterior shading devices, and roof area and its construction (Lam et al., 2005).

Several studies show that decisions that are made earlier in the design process have more potential to reduce overall building LCE (Basbagill et al., 2013; Pacheco et al., 2012). According to Li et al. (2013), the most common measures used to achieve energy efficiency in the built environment can be divided into three categories: (i) External heat transfer (building envelope), (ii) Internal heat gain (people, lighting, plug loads, etc.,), and (iii) Building system services (mechanical systems, elevators). Amongst these three categories, the building envelope has the most impact on the overall building energy (Pacheco et al., 2012).

2.2.2. Components of the building envelope

Building orientation: Aligning the major axis of the building after carefully considering the relationship of the building, with its physical surroundings and the sun path - during the design stages will significantly help in lowering the end-use energy consumption (Morrisey et al., 2011). Choosing the best orientation for a building, is considered the most effective passive design strategy for saving energy (Pacheco et al., 2012). A correctly oriented building, requires lesser heating and cooling when compared with other buildings, because of lesser solar heat gain. In addition, these buildings will be able to capture maximum light and reduce the internal loads due to artificial lighting (Pacheco et al., 2012). From an energy perspective, the orientation of a building controls the (i) amount of daylight entering the building, and (ii) heat gain/loss through the building envelope (Morrisey et al., 2011). As a general rule of thumb, the longer wall sections are oriented to the south (Pacheco et al., 2012).

Walls: The amount of thermal insulation used in the exterior walls, significantly controls the amount of conductive heat gain/loss through the building envelope. (Li et al, 2013). The selection criteria of thermal insulation are heavily dependent upon the thermal conductivity and thermal inertia of the material. The low thermal conductance or high thermal resistance in these materials slows the rate of heat flow into or out of a building (Sadineni et al., 2011). Applying optimum insulation thickness in the building helps in drastically reducing HVAC loads. Commonly used insulation materials include mineral wool, fiberglass batts, extruded polystyrene, expanded polystyrene, polyurethane etc.

However, these materials have high embodied impact due to their large ozone layer depleting potential and global warming potential.

Roofs: The roof of a building constitutes an important component of the building envelope, that is extremely prone to heat gain. This mainly occurs due to their entire surface area being exposed to solar radiation and environmental change for long durations of time (Sadineni et al., 2011). The roofs, massively influence the indoor occupancy comfort level and the overall thermal performance of a building. In recent times, a huge variety of roofing options have been developed to suit our needs. Some roofing options include masonry roofs, lightweight roofs, ventilated and micro-ventilated roofs, cool roofs and green roofs.

2.3. Building energy trade-offs

There are several studies related to building lifecycle energy. Most of these studies focus upon the operational energy consumption in buildings and measures to reduce OE, while very few of them address the EE aspect (Praseeda et al., 2016). This is because 83% of a buildings LCE consumption is concentrated upon its operational phase (Scheuer et al., 2003). In addition, most of these studies ignore/neglect the EE aspect of building energy consumption because of the following reasons: (i) inconsistent or inaccurate EE data, (ii) limited number of tools to evaluate EE, and (iii) no direct benefits related to building construction costs (Wang et al., 2005). However, it is important to understand that the implementation of OE reduction measures is usually associated with high IEE consumption (Zhang et al., 2016; Ramesh et al., 2010). For example, several studies suggest providing higher insulation on the exterior walls are roofs, using multiple pane windows with coatings (low-emissivity), changing the window to wall ratio (WWR) or employing additional shading devices (Cabeza et al., 2014). These energy conservation measures help in dramatically reducing building OE (Peippo et al., 1999). However, in most cases, the IEE payback time of these energy-efficient measures are much longer than the buildings lifecycle; this causes detrimental impacts on the environment and results in being counter-productive to our objective of reducing energy consumption (Chastas et al., 2016; Cabeza et al., 2014; Ramesh et al., 2010).

Several studies also show that measures that are applied to reduce certain OE components might have a negative impact on the remaining OE components. For example, minimizing the energy used for heating might have a negative implication on the energy required for cooling or artificial lighting (Goia, 2016). Another study conducted by Yohanis and Norton (2002) found that the IEE of a building could be around 67% of its OE for a 25-year period. Nonetheless, the energy spent to construct a building verses the energy spent on operating the building creates a paradox (Copiello, 2016). Therefore, overall building energy reduction must carefully address trade-offs between both operating and embodied energy components (Treloar, 1997).

2.3.1. Impact of added insulation on building LCE

Literature consists of numerous studies that suggest using additional insulation in a building as an OE reduction measure. Rodrigues and Freire (2017) conducted a comprehensive analysis of using alternative insulation thicknesses (no insulation, 40 mm, 80 mm, and 120 mm of expanded polystyrene) to identify the most optimum solution. The case study was conducted on a single-family house and an apartment complex that were located in Coimbra, Portugal. Both the EE and OE impacts were assessed for a period of 50 years. The EE impacts of the single-family house and apartments were found to account for 26-57% and 25-49% of the total LCE respectively. The overall energy reduction that was achieved by using thicker insulation was lesser than 3%. The results of their study also showed that increasing the insulation thickness to 120 mm had embodied impacts that were greater than operational impacts. In conclusion, the study observed that adding extra insulation beyond a certain tipping point can result in higher EE impacts, without significant reduction in OE.

Fay et al. (2000) conducted a study to determine the impacts of increasing insulation on the overall building energy consumption. The study uses an Australian based, two-storey residential building as a case study to demonstrate these impacts. The base scenario has exterior walls that have 50 mm thick fiberglass insulation. It was observed that the base scenario had an EE of 35.4 MJ/m^2, OE of 300 MJ/m^2 and LCE of 140.4 MJ/m^2 A study case with higher insulation was created as a variation from the base case. The insulation was increased from the base case to R-2.5 bulk insulation in the walls, R-1 insulation in the roofs and R-4 insulation in the ceilings. For a building lifespan of

100 years, it was found that for the base case with added insulation, the EE was 36.5 MJ/m^2, OE was 210 MJ/m^2 and LCE was 132.5 MJ/m^2. It was found that the overall net-lifecycle saving due to the use of additional insulation was less than 6%. Therefore, implying that other strategies might need to be considered before increasing the insulation in a building.

Mithraratne and Vale (2004) conducted a LCEA on a timber-framed house located in New Zealand. Additional layers of insulation were added to the timber-frame house as an energy saving measure. Upon comparing LCE for a period of 100 years, it was observed that the base case with 94 mm thick fiberglass insulation had an EE of 4425 MJ/m^2, space heating requirement of 7736.4 MJ/annum and LCE of 17017MJ/m^2. The second, more insulated version of the building used 25 mm polystyrene as insulation. This version of the building had its EE increased to 4764 MJ/m^2, while the space heating requirement decreased to 7048.6 MJ/annum. Interestingly, the total building LCE decreased to 16237 MJ/m^2. The third super insulated version, doubled the insulation used in the base case. In this case, the EE increased to 5041 MJ/m^2 while the space heating and LCE requirement decreased to 4172.4 MJ/annum 11832 MJ/m^2 respectively.

Sartori and Hestnes (2007) conducted a case study on six versions of a building (one conventional, four low energy and one self-sufficient) to evaluate their LCE demand. Here, it was observed that the self-sufficient version of the building consumed more energy than certain low-energy versions. This can be attributed to the high embodied energy, that was required in order to integrate the energy saving measures into the self-sufficient version. Several other studies suggest using a thicker layer of insulation to lower the consumption of OE. However, the high IEE consumption might take a long time to payback and sometimes might take longer than the building lifespan.

The study conducted by Crawford and Treloar (2005) shows that the EE consumed by a building is usually no more that 15% of the total energy use of a building for a 50-year lifespan. However, in a well-insulated energy efficient building; the EE can account towards 40% of the total energy consumption therefore even exceeding OE. Therefore, most often the excessive use of active and passive technologies to reduce OE, might become counter-productive. In these cases, it becomes important to quantify the extent until which OE can be reduced, before the EE starts increasing significantly; thereby increasing the overall LCE during its lifetime (Ramesh et al., 2010).

Design improvements made to the building envelope to improve thermal efficiency are usually associated with higher material production energy intensity and construction burden (Balouktsi and Lutzkendorf, 2016; Chastas et al., 2016). While material changes might cause a significant decrease in OE consumption, they lead to insignificant savings in terms of building LCE. In certain cases, they can even result in higher building LCE due to increase in EE (Crawford et al., 2016).

2.3.2. Impact of changing window to wall ratio (WWR) on building LCE

Thermal and visual comfort in a built environment is achieved through air-conditioning and artificial lighting respectively (Li et al., 2005). Recent studies show that air-conditioning accounts for 40-60% of electricity use, while lighting accounts for 20-30% (Li et al., 2005). Both these loads have a direct relationship with the thermal performance of the building envelope. The building envelope is a simple combination of transparent (windows) and opaque surfaces. The ratio between the transparent and opaque surfaces have a major impact on the energy balance (with implications on heating and cooling loads), and daylight availability (with implications on artificial lighting loads) in a building (Goia, 2016; Peippo et al., 1999).

The overall thermal transfer value (OTTV) of a building envelope is controlled by two factors, they are (i) solar heat gain and (ii) WWR (Li et al., 2005). More recently, there has been a trend of incorporating daylighting into the building design. Exploiting the availability of natural light has the tremendous potential of reducing artificial lighting loads (Goia, 2016; Alghoul et al., 2015). Having a large WWR causes higher heat conduction through the glass windows and lower heat conduction through the opaque walls and vice-versa (Li et al., 2005). This results in increasing the solar heat gain in a building- contributing towards increased space cooling requirements. While several studies claim that this increased cooling load can be offset by the daylight induced savings it is also important to understand that these savings might vary based on the temperature and climate of a specific region (Kalogirou and Bojic, 2000; Yin et al., 2011). The study performed by Yohanis and Norton (2002) found that having a WWR of 15%has the lowest OE demand. In hot regions, majority of the cooling loads occur due to heat gain through windows. Therefore, increasing the WWR becomes detrimental, since it contributes towards approximately 40-50% of the total heating load in winter, and 20-30% of the cooling loads in summers (Yin et al., 2011). On the other hand, the consequence of reducing the WWR is less natural light, thereby resulting in an increase of lighting loads (Utama and Gheewala, 2009).

In addition, to conflicting impacts on OE components, the WWR is also associated with EE implications. This implies that careful material and component selection with appropriate thermal and optical properties is necessary to reduce heating, cooling and lighting loads (Goia, 2016). According to the studies conducted by Utama and Gheewala (2009) and Yohanis and Nortan (2002) it was found that reducing the WWR did not consume additional EE. This may be attributed to the reduction of the windows (amount of glass) and window frame (timber) quantities. This reduction was sufficient to adjust the additional EE for the material in the wall construction (brick). However, in certain cases, the EE associated with a particular wall assembly is much higher than that of glass. Here, the EE shows a significant increase with decrease in WWR. However, the results of the study performed by Giordano et al. (2015) were contradictory to the study performed by Utama and Gheewala (2009). The study by Giordano et al. (2015) found that increasing the WWR increased the EE for different wall construction assemblies. This was mainly due to the high IEE associated with glass and aluminum products, that are used in windows. Therefore, carefully addressing the conflicting impacts of different LCE components becomes an important step in improving the performance of a building (Li et al., 2005).

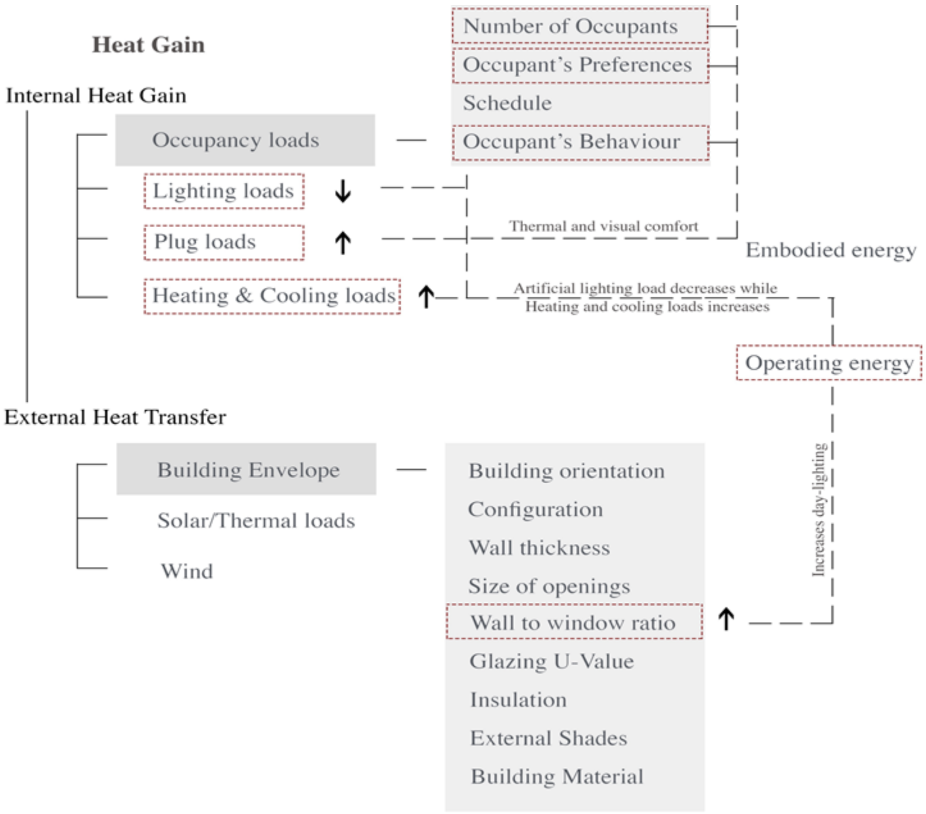


Figure 1 WWR interdependencies of building energy components

2.3.3. Impact of changing amount of solar shading devices on LCE

Solar shading devices are overhangs that are used to protect the transparent surface of a building envelope from solar radiation by blocking the unwanted energy flow into a building (Bellia et al., 2013). These devices increase the efficiency of the façade by helping us dynamically control the solar heat gain and daylight that enters the building (Goia, 2016). Shading devices have different implications on the heating, cooling and lighting loads of a building (Li et al., 2016). Literature shows that the use of external shading is the most effective in reducing building loads amongst several other passive energy-reducing strategies (Li et al., 2016). Nearly 80% of the solar heat gain can be reduced by shading all the fenestrations in a building; this accounts to 8% of the building cooling loads (Bellia et al., 2013; Ebrahimpour and Maerefat, 2011). A major fraction of a building's thermal load is due to solar heat gain, in hot climatic regions; thereby making external shading devices extremely useful in these regions (Pacheco et al., 2012). The choice of shading device depends upon the size of the window (influences overhang depth), orientation of the building and the apparent sun path (Bellia et al., 2013). Overhangs on the southern façade and louvres on the east-west façade help in achieving optimal results. While solar shading helps in reducing cooling energy demand, it leads to an increase in energy demands for both heating and lighting systems. This is because shading devices block solar heat radiation and the entry of natural light into the building; thereby increasing our heating loads in the winters and lighting loads (Bellia et al., 2013; Pacheco et al., 2012).

Adding additional shading structures generally require additional labor, and materials that are associated with higher embodied energy (Huang et al., 2012). The CO_2 emissions payback period, has a negative effect when shading systems are implemented. For example, in the study conducted by Huang et al. (2012) it was found that 440 tons of building materials was utilized to cover a window glazing area of approximately $1838m^2$. This additional need for building materials lead to high amounts of energy investments and CO_2 emissions. Furthermore, shade depths are determined by the window heights (Pacheco et al., 2012). Therefore, larger windows require more material for providing optimum levels of shading. Understanding the balance between external shades on heating, cooling, lighting and EE demands is important for overall building energy reduction.

2.4. Studies on embodied and operating energy trade-offs

Utama and Gheewala (2009) conducted a study to evaluate the EE impact of using single vs double wall for a high-rise residential building in Jakarta, Indonesia. They performed a building LCEA, to ascertain the impact of using different building envelope construction assemblies on the building's HVAC loads. The double walls constituted of clay bricks, gypsum plaster board and an air gap in between, while the single wall comprised of clay bricks. The EE of the building was calculated using process-based method, while the OE was computed using Ecotect. It was found that the EE of the double wall envelope was 79500 MJ and that for single wall envelope was 74.5 MJ. The OE consumption for the double wall envelope was 194000 MJ and single walls envelope was 383700 GJ. The overall LCE of the building was 282900 GJ for the double walls and 460000 MJ for the single walls. Thereby, implying that even though the EE was higher for the double wall system, the overall LCE was much lesser.

Crawford et al. (2010) calculated the LCE requirements for eight residential construction assemblies over a 50-year period. The system boundary in this study included the IEE, REE, DEE and the OE of the building. An input-output model, using the Australian energy database was used to calculate EE, while the OE was calculated using the TRNSYS software. Here, different material that were used in each assembly was applied to a ‘box’ that had an area of 50 m^2 with 3m high walls. Subsequently, three different sized boxes were subjected to a sensitivity analysis. The results of this analysis showed that the difference in the space conditioning loads of these boxes. In conclusion, the study determined that using an assembly that has high IEE, might improve the thermal performance of the assembly and lessen material replacement, consequently reducing the LCE of a building.

Certain studies have made recommendations, to enhance the existing methods used to perform building LCEA, which are relatable to our study. For example, the study by Basbagill et al. (2013) emphasizes upon the vitality of making effective design decision during the initial conceptual stages. The building information modeling (BIM) tools are used to inform designers regarding the energy consumption of a particular building material. In this manner, BIM enabled decision making helps designers identify the combination of materials that helps in reducing the environmental impact. Shrivastava and Chini (2012) performed a similar study to identify the impacts of IEE upon material selection with the help of BIM tools to improve LCEA related decision making.

2.5. Tools used for building lifecycle energy analysis

Input data for most of the tools used in LCA calculations include the building geometry and orientation, ventilation and air-tightness, building envelope characteristics, shading devices, building system services and human factors (Santos et al., 2014). Climate data is usually obtained from the International Weather Energy Calculation database (Santos et al., 2014). In most cases, Energy Plus (simulation tool), is used to calculate the OE of a building. This tool was developed upon the DOE-2 platform and has the same accuracy as DOE-2 (Coakley et al., 2014; Wilde et al., 2010). However, the input files of these simulation tools are not very well integrated with existing BIM tools, thereby limiting their use during early design stages (Basbagill et al., 2013). To resolve this issue, Autodesk developed plug-in Green Building Studio (GBS) which is used to perform energy simulations within the BIM interface. In doing so, the BIM software does not need to communicate with another software, thereby eliminating the issue of interoperability. In addition, Abanda and Byers (2016) conducted a study to verify the accuracy of results obtained from GBS with another simulation tool (Ecotect). The outcome from both these tools were similar with very insignificant variations.

3. PROBLEM STATEMENT

Several studies have investigated the lifecycle energy requirements of buildings. Most of these studies typically address the implications of OE reduction measures on EE, on an aggregated building level. In addition, a limited number of studies explore the effect of using different construction assemblies on EE. According to literature, there is a lack of studies that evaluates EE impacts caused due to both - OE reduction measure and construction assembly type. Therefore, quantifying the individual influence of each OE reducing measure across different construction assemblies on EE is still required (Crawford et al., 2016; Ajayi et al., 2015; Ibn-Mohammed et al., 2013).

4. RESEARCH GOALS AND OBJECTIVES

A building that is considered to be carbon neutral or zero energy during its operational phase is usually constructed using energy-intensive material that has high EE impacts (Ajayi et al., 2015). Therefore, the goal of this study is to enable holistic building lifecycle analysis that informs energy optimization decision making. This goal will be achieved through the following research objectives:

- Quantify and compare trade-offs on EE demand, caused by OE reduction measures for different building assembly types. This will be achieved by performing an energy simulation on ASHRAE’s 90.1-2016 benchmark building in a heating and cooling dominated region.
- Compute EE use (EE-factor) per unit of OE saving for different OE reduction measures across construction assemblies.

5. RESEARCH METHODS

This study was conducted in four steps:

(i) Conducting a rigorous review of related literature: A systematic review of literature was performed to identify OE reduction measures and commonly used building assembly types in commercial buildings. The Google scholar database was used as our primary electronic source of information. In addition, resources from the Texas A & M university library such as the ASHRAE standard 90.1-2016, was also reviewed to gather related information. The search in Google scholar was performed using keywords such as building lifecycle energy, operating energy, embodied energy, building envelope, construction assemblies, net-zero energy buildings, building information modelling, energy simulation tools, etc., to create a sample of published studies that were most relevant to our study. This initial search resulted in finding over 4500 studies in the form of journal papers, conference proceedings, government documents, material specification reports, industry research reports, Ph.D. dissertations etc., from the year 1997 to 2018.

After an initial screening of these studies, some of them were excluded from the review due to a mismatch of the main points being reviewed in this paper, lack of details and failure to comprehensively address the concept of reducing building LCE. This failure to understand the definition of building LCE can be observed in several studies, since they have not holistically included the evaluation of EE, OE, and other forms of renewable energy in their LCEA calculations (Hernandaz and Kenny, 2010).

As a result, our search was narrowed down to only include studies based on our inclusion criteria. Eventually, this search resulted in finding 109 studies, that were crucial in providing us with a comprehensive understanding of the topic. The common measures used to reduce operating energy by changing building envelope parameters, that were identified in literature are shown in Table 1. It was found that these measures need to be carefully selected, to improve the thermal performance of the building envelope and reduce OE consumption. The gathered information was then organized in the form of a matrix (as seen in Table 1) with the name of the study listed on the Y-axis and the corresponding OE reduction measure listed on the X-axis. Furthermore, details regarding various OE reducing building materials and their construction assemblies were also collected as a part of the literature review.

Table 1 Measure taken to reduce operating energy by corresponding study

Study	**Building Component**											
	Walls							**Windows**			**Roofs**	
	Orientation	**Thermal properties of material**	**Wall thickness**	**Wall systems**	**Wall insulation (type or thickness)**	**Wall thermal mass**	**External finishes / Treatments / Paint**	**Glazing / Number of panes/ Window type**	**Wall to window ratio / Window size**	**U-value (Thermal transmittance)**	**External shading devices / Roof overhangs**	**Roof insulation (type or thickness)**
Harkouss et al.,			*		*			*	*			*
Chastas et al., 2016	*				*		*	*		*		
Lau et al., 2016								*			*	
Zhao et al., 2016	*				*			*		*		
Zhu et al., 2013				*				*			*	*

Table 1 Continued

Study	Building Component											
	Walls							Windows			Roofs	
	Orientation	Thermal properties of material	Wall thickness	Wall systems	Wall insulation (type or thickness)	Wall thermal mass	External finishes / Treatments / Paint	Glazing / Number of panes/ Window type	Wall to window ratio / Window size	U-value (Thermal transmittance)	External shading devices / Roof overhangs	Roof insulation (type or thickness)
Stevanovic, 2013												
Susorova et al., 2013	*								*			
Pacheco et al., 2012	*				*			*	*	*		
Kaynakli, 2012					*							
Attia et al., 2012	*		*		*			*	*		*	*
Asadi et al., 2012				*	*			*				
Chesne et al., 2012					*							
Zinzi et al., 2012							*					
Ramesh et al., 2012			*	*	*					*		*
Shi, 2011					*							
Sadineni et al., 2011		*		*	*	*	*	*			*	*
Al-Tamimi et al., 2011											*	
Jelle, 2011				*	*					*		
Shameri et al., 2011								*	*		*	
Zamella et al., 2011								*	*		*	
Gasparella et al., 2011	*							*	*		*	
Leskovar and Premrov,	*							*	*	*		
Jaber and Ajib, 2011	*							*	*			
Sozer, 2010	*				*			*	*		*	
Castleton et al., 2010										*		*
Hassouneh et al., 2010	*							*	*			
Aste et al., 2010					*	*						
Singh and Garg, 2009		*						*		*		
Utama and Gheewala,		*	*	*						*		
Ochoa and Capeluto,	*							*	*	*	*	
Bahaj et al., 2008								*				
Yu et al., 2008					*			*	*		*	
Masoso and Grobler,					*							
Poirazis et al., 2008								*	*			
Xing et al., 2008		*		*						*		
Li and Wong, 2007											*	
Wang et al., 2007									*	*	*	
Chitherlet and Defaux,					*							
Lollini et al., 2006					*							*
Persson et al., 2006	*							*	*			
Marceau and VanGeem,				*								
Wang et al., 2005	*			*				*	*		*	

Table 1 Continued

Study	Building Component											
	Walls							Windows			Roofs	
	Orientation	Thermal properties of material	Wall thickness	Wall systems	Wall insulation (type or thickness)	Wall thermal mass	External finishes / Treatments / Paint	Glazing / Number of panes/ Window type	Wall to window ratio / Window size	U-value (Thermal transmittance)	External shading devices / Roof overhangs	Roof insulation (type or thickness)
Christenen et al., 2005	*					*		*	*	*	*	
Cheung et al., 2005					*	*	*	*	*		*	
Mitraratne and Vale,					*							
Oral et al., 2004			*		*			*	*	*		
Caldas and Norford,				*					*			
Comakli and Yuksel,					*							
Bojic et al., 2002					*							
Scofield, 2002	*		*		*	*		*	*	*	*	
Oral and Yilmaz, 2002	*							*	*	*		
Balaras et al., 2000					*		*	*			*	
Bouchlaghem, 2000	*	*	*		*		*	*	*		*	
Chan and Chow, 1998					*				*	*	*	

In addition, the literature review also helped us identify common materials that were used for enhancing the performance of the building, as shown in Table 2. The materials were divided into three categories, they are walls, windows, and roofs. Several material options that were found in literature are listed below these categories. This material list helped us create various wall and roof assemblies for our study (Table 2).

Table 2 Common material used in commercial construction

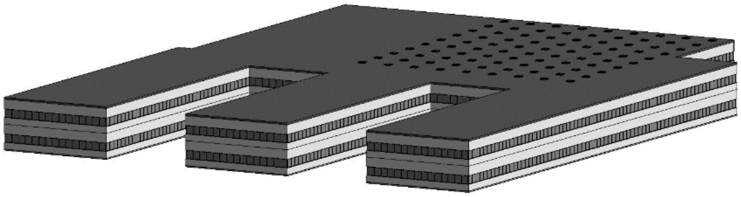
Building System	Material Options
Walls	
Structural system	Steel stud framing (cold formed metal)
	Concrete masonry units
Sheathing	Gypsum sheathing, 1/2" exterior grade
Drywall	Gypsum board

Table 2 Continued

Building System	Material Options
Walls	
Insulation	Expanded polystyrene
	Extruded polystyrene
	Fiber glass
	Mineral wool
	Cellulose
	Rigid foam
Exterior finishes	Brick Veneer, 4"
	Concrete panels, 2"
	Stone Veneer, 2" (limestone)
	Pre-cast metal panels
	Paint
Windows	
Window or door frames	Aluminum
	Fiber glass
Window glazing	Double glazed
	Gas filled (Argon filled)
	Vacuum glazed
	Aerosol gels
	Low- e coated
	Reflective coating
Roofs	
Structural Systems	Concrete, supported by steel joists and deck
Exterior finish	Asphalt shingles
	Cement flooring tiles
	Composite shingles
	Clay tile or Modified bitumen
Roof insulation	4" EPDM insulation
	Extruded polystyrene
	Polyurethane
Floors	
Flooring systems	4" concrete slab
Floor finish	Carpet
	Tile, vinyl tile
	Cement finished floors
	Terrazzo

(ii) Developing the Benchmark model: To quantify and compare the building lifecycle energy associated with different construction assemblies, we created a benchmark model based on ASHRAE 90.1, 2016 standards using a BIM enhanced approach. The benchmark model was created using Autodesk Revit as the BIM authoring tool. The benchmark model is a two-floor educational building of approximately 210,900 ft^2. Table 3, gives us a detailed description of the benchmark model. In this study, we consider the ASHRAE 90.1-2016 benchmark model to be a stand-alone building without considering its surrounding environment. The system boundary in the study considers only heating, cooling and lighting loads as OE.

Table 3 Details of ASHRAE 90.1-2016, benchmark model

Building component	Description
Building Form	
Window height and location	4'6" continuous band
Shading devices	None
Floor to Floor height	13'
Floor construction	6" concrete slab +carpet finish
Exterior wall construction	Steel framed walls (2x4, 16IN OC) Stucco + Insulation + Gypsum sheathing
Roof construction	Built up roof Roof finish + Insulation + Metal deck
Skylights	4'X4' (total 54)

(iii) Applying OE reduction measures to the benchmark model: After creating the benchmark model, we modelled eight variations of construction assemblies for the external wall. For each construction assembly, we would apply an OE reducing measure identified in literature to calculate overall building LCE. The commonly identified categories of OE reduction measures that were identified in literature include (i) building orientation, (ii) window glazing type, (iii) window shading, (iv) window-wall ratio, and (v) assembly of the roof construction. Parameters belonging to each category were then varied and their subsequent impact on the OE and EE of the building was recorded. The study covers 60 years of the building lifecycle, located in two different climate zones in the United States. Therefore, the building's energy performance is evaluated in a (i) heating dominated region (Chicago, Illinois), and, (ii) cooling dominated region (Houston, Texas), for each measure across different construction assemblies. These climate zones were specifically chosen based on the degree-days concept. The heating and cooling degree days (HDDs and CDDs) are used as a measure to determine the severity of winter and summer conditions in a geographic location. These HDDs and CDDs of a region, directly impact the energy requirement in a building (Li et al., 2013). According to the ASHRAE 90.1, 2016 standards the climates for Chicago and Houston are classified into climate zones 5A cold-humid climate and 2A hot-humid climate respectively. Therefore, the difference in the number of HDDs and CDDs between Houston and Chicago will help us study the variation in the results for different climate zones.

Autodesk Revit Green Building Studio (GBS) is used to compute the building's OE requirements while Autodesk Tally is used to compute the EE requirements. Both these tools, are plug-ins that are integrated with Autodesk Revit. However, when the energy settings of the benchmark model were exported from Autodesk Revit and imported into GBS there were some inaccuracies in the construction details of the envelope assemblies. To resolve this issue, pre-defined constructions with the desired U-values were selected from the GBS interface to run the energy simulations and obtain the results. The default weather files available on GBS, for the specified locations were used to run the simulations. Furthermore, simulations were also performed on two exterior wall assemblies using E-quest to verify the results obtained from GBS.

(iv) Interpreting data obtained from the energy simulations: The difference in EE for each OE reduction measure, helped us develop an evaluation criterion that would give us information regarding the most effective OE reduction measure to the least effective measure, for a specific construction assembly. Appendix A, shows us a list of materials that will be used in a combination, to create construction assemblies for the purpose of this study. The R-values for the hot-humid climate of Houston, range from R-13 to R-27, while the R-values for the cold-humid climate of Chicago vary from R-19 to R-30.

6. RESULTS

As The results generated from this study can be categorized into (i) heating dominated region (climate zone 5A), and (ii) cooling dominated region (climate zone 2A). The categories have further sub-categories for four different construction assemblies. Each of these assemblies are then analyzed based upon their (i) orientation, (ii) glazing system, (iii) shading, (iv) WWR, and (v) roof construction. These energy simulations were conducted to collect data regarding the trade-offs between the various OE and EE components on an annual basis.

The ASHRAE 90.1-2016 baseline benchmark model was simulated based on real measurements and construction assemblies that were specified in their prescriptive codes for climate zone 2A and 5A (Table 5.5-2 and Table 5.5-5 of ASHRAE standard 90.1-2016). According to the Normative Appendix G of ASHRAE standard 90.1-2016, the baseline energy consumption for the benchmark model is calculated by averaging the results obtained by rotating the entire building to 90, 180 and 270 degrees and its actual orientation. Tables 4-11, show the results for the annual energy use intensity (EUI) and total embodied energy in kBtu per ft^2 per year, for study cases with different OE reduction measure applied across varying construction assemblies.

The orientation of the building, is the first study case category that was analyzed. The building was rotated in increments of 45^o to cover all the eight quadrants. According to the ASHRAE standard 90.1-2016, the 45^o angle is the smallest rotational increment, that would have a noticeable influence on the EUI of a building. These increments are sufficient to analyze the sensitivity of a building to its orientation. The positive values denote a clockwise rotation, while the negative values denote a counter-clockwise rotational angle. Secondly, the impact of various glazing systems on the overall building energy was analyzed. The different glazing systems used in this study were low-e glazing, insulated reflective low-e glazing, double-pane low-e glazing and triple-pane low-e glazing. Thirdly, the impact of external shading on the overall building loads was calculated. The window shades were modelled with depths of 9 in (1/6 window height), 13.5 in (1/4 window height) 18 in (1/3 window height), 27 in (1/2 window height), and 36 in (2/3 window height). Fourthly, the impact of changing the WWR was on the final building loads was studied. The WWR was varied with values of 15%, 30%, 40% and 50%. Finally, the impact of varying the level of insulation in the roof assembly on the overall building load was calculated. The insulation in the roof had different materials such as extruded polystyrene insulation, expanded polystyrene insulation, rigid foam insulation and polyurethane board insulation. The R-value of the roof was varied between R-30 and R-45 and the subsequent impacts on OE and EE was simulated.

As predicted earlier, the EUI of all the simulated study cases is much lesser than that of the baseline, except when the WWR is between 40-50%. This confirms that all of the OE reduction measures are helpful in reducing building loads. Later, the operating and embodied energy demand of the baseline benchmark model was compared with the alternative construction assemblies to generate the gradient diagram. For Figures 2-5 and 7-10, the X-axis of this diagram represents the percentage of OE or EE that is added or reduced when compared with ASHRAE’s 90.1-2016 benchmark model, while, the Y-axis is representative of each OE reducing measure that was applied to the model. The X-axis of these figures use upper-case captions to denote major categories, while using lower-case captions for their sub-categories. These figures would help us understand the relationship between conflicting energy reducing measures.

The percentage of OE and EE difference is calculated by comparing the energy demand in the study case to the ASHRAE 90.1-2016 benchmark model. The % of OE difference is calculated using Equation 1,

$$\text{change } (\Delta) = \text{EUI}_{\text{of study case}} - \text{EUI}_{\text{of ASHRAE 90.1-2016 baseline}}$$

$$\text{\% of OE difference} = (\text{change} / \text{EUI}_{\text{of ASHRAE 90.1-2016 baseline}}) \times 100 \qquad \text{(Equation 1)}$$

While, the % of EE difference is calculated using Equation 2,

$$\text{change } (\Delta) = \text{EE}_{\text{of study case}} - \text{EE}_{\text{of ASHRAE 90.1-2016 baseline}}$$

$$\text{\% of EE difference} = (\text{change} / \text{EE}_{\text{of ASHRAE 90.1-2016 baseline}}) \times 100 \qquad \text{(Equation 2)}$$

The % decrease is represented using negative numbers, while the % increase is represented as positive values. The EE factor is calculated as the amount of EE spent per kBtu of OE saved. This value is obtained by dividing the EE with OE (as seen in Tables 4-11).

6.1. Heating dominated region (climate zone 5A)

As seen in Table 4, the ASHRAE 90.1-2016 benchmark model has a total EUI of 80.43 kBtu/ft^2/year and embodied energy consumption of 8.15 kBtu/ft^2/year.

Table 4 Summary of OE and EE variation, along with EE factor for wall assembly 1b, in a heating dominated region

MEASURES FOR OE REDUCTION	ASSEMBLY 1b (U=0.04)				
	OPERATING ENERGY	EMBODIED ENERGY	DIFFERENCE		
	EUI	EE/AREA	% of OE DIFFERENCE	% of EE DIFFERENCE	EE factor EE/OE
	kBtu/ft^2/year	kBtu/ft^2/year			
ASHRAE Benchmark (U=0.51)	80.436	8.155			
Most optimum	66.655	10.366	-17.134	27.122	0.156
ORIENTATION					
(-)90	77.860	8.260	-3.202	1.287	0.106
(-)45	78.162	8.260	-2.827	1.287	0.106
(+)180	79.838	8.260	-0.744	1.287	0.103
(+)90	77.709	8.260	-3.391	1.287	0.106
(+)45	79.233	8.260	-1.495	1.287	0.104
GLAZING					
Low-e	75.648	8.271	-5.953	1.431	0.109
Insulated reflective low-e	73.663	8.274	-8.421	1.469	0.112
2-pane low-e	73.034	8.340	-9.203	2.273	0.114
3-pane low-e	72.460	8.392	-9.916	2.910	0.116
SHADING					
1/6 window height	79.577	8.265	-1.069	1.349	0.104
1/4 window height	79.666	8.268	-0.958	1.389	0.104
1/3 window height	79.173	8.271	-1.570	1.429	0.104
1/2 window height	78.625	8.278	-2.251	1.510	0.105
2/3 window height	78.475	8.284	-2.439	1.590	0.106
WINDOW TO WALL RATIO					
15%	71.649	8.601	-10.924	5.478	0.120
30%	79.184	8.205	-1.557	0.615	0.104
40%	81.268	8.025	1.035	-1.586	0.099
50%	83.390	7.913	3.672	-2.959	0.095
ROOF CONSTRUCTION					
Q1	76.477	8.460	-4.922	3.747	0.111
Q2	76.391	8.632	-5.029	5.860	0.113
Q3	75.454	8.676	-6.194	6.392	0.115
Q4	75.360	10.089	-6.311	23.721	0.134

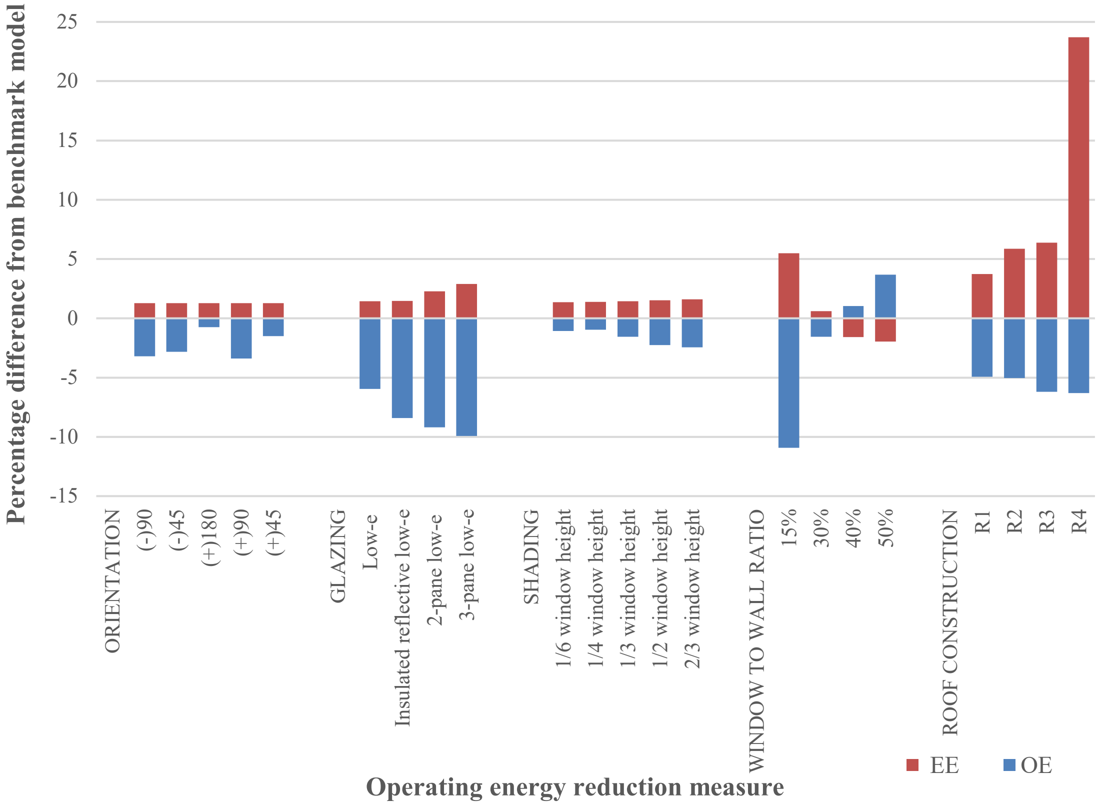


Figure 2 EE variation caused by applying OE reduction measures on Assembly 1b

Upon changing the orientation of the building (Figures 2-5), no differences were observed in the EE demand across construction assemblies. This is mainly because additional material was not added to the baseline model.

Table 5 Summary of OE and EE variation, along with EE factor for wall assembly 2b, in a heating dominated region

MEASURES FOR OE REDUCTION	ASSEMBLY 2b (U=0.039)				
	OPERATING ENERGY	EMBODIED ENERGY	DIFFERENCE		
	EUI	EE / AREA	% of OE DIFFERENCE	% of EE DIFFERENCE	EE factor EE/OE
	kBtu / ft^2 /year	kBtu / ft^2 /year			
ASHRAE Benchmark (U=0.51)	80.436	8.155			
Most optimum	66.413	10.374	-17.434	27.216	0.156
ORIENTATION					
(-)90	77.589	8.264	-3.539	1.344	0.107
(-)45	77.831	8.264	-3.238	1.344	0.106
(+)180	79.612	8.264	-1.025	1.344	0.104
(+)90	77.425	8.264	-3.743	1.344	0.107
(+)45	78.892	8.264	-1.919	1.344	0.105
GLAZING					
Low-e	75.409	8.277	-6.249	1.506	0.110
Insulated reflective low-e	73.278	8.280	-8.900	1.542	0.113
2-pane low-e	72.678	8.345	-9.645	2.330	0.115
3-pane low-e	72.177	8.398	-10.268	2.985	0.116
SHADING					
1/6 window height	79.221	8.269	-1.510	1.406	0.104
1/4 window height	79.372	8.271	-1.323	1.431	0.104
1/3 window height	78.868	8.276	-1.949	1.485	0.105
1/2 window height	78.271	8.282	-2.692	1.565	0.106
2/3 window height	78.056	8.287	-2.960	1.627	0.106
WINDOW TO WALL RATIO					
15%	71.223	8.609	-11.453	5.571	0.121
30%	78.897	8.204	-1.914	0.607	0.104
40%	81.072	8.053	0.791	-1.243	0.099
50%	83.211	7.916	3.449	-2.922	0.095
ROOF CONSTRUCTION					
Q1	76.250	8.465	-5.205	3.802	0.111
Q2	76.149	8.637	-5.329	5.915	0.113
Q3	75.213	8.680	-6.494	6.447	0.115
Q4	75.112	10.095	-6.619	23.794	0.134

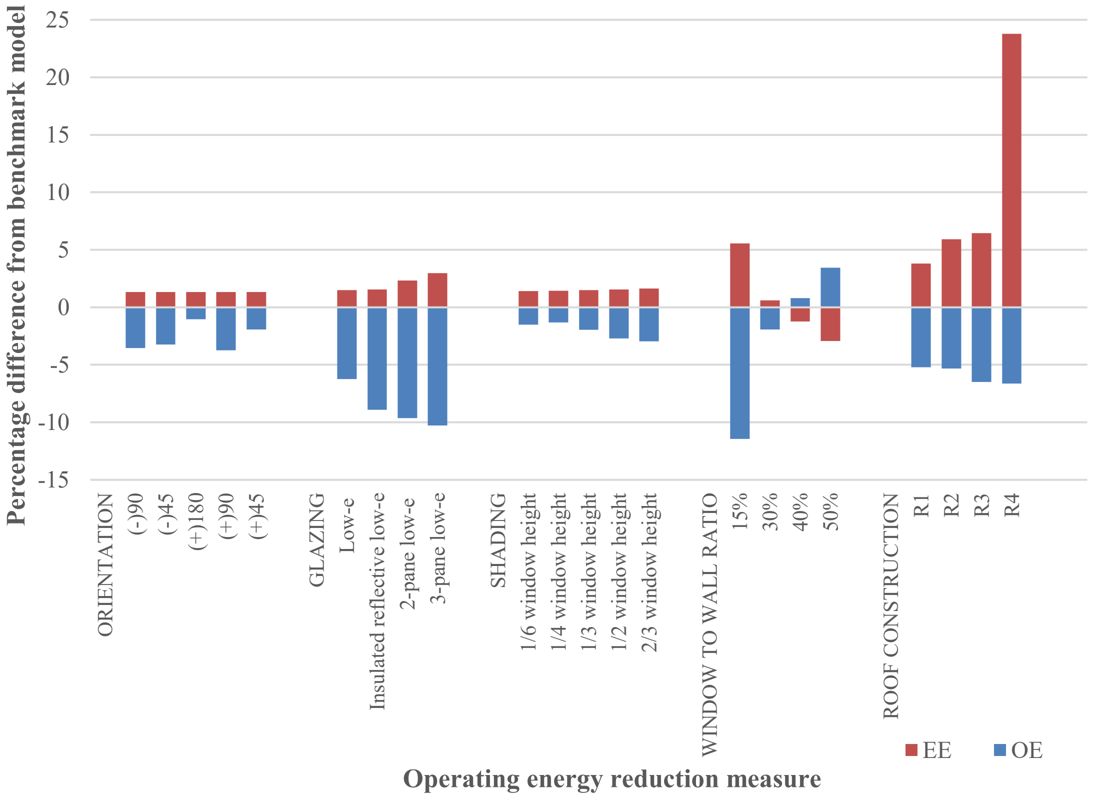


Figure 3 EE variation caused by applying OE reduction measures on Assembly 2b

The second OE reduction measure of changing the glazing system for wall assembly 1-4 showed the following results. For wall assembly 1b (Table 4) and 2b (Table 5), we observed 6-10% decrease in OE for 1.5-3% increase in EE. For wall assembly 3b (Table 6), we found that 6.6-10.5% decrease in OE results in increasing the EE from 2.5-4% (Figure 4). In the case, of wall assembly 4b (Table 7), we noticed that 7.5-11.5% decrease in OE subsequently increases the EE from 3-4.5% (Figure 5). While we compare the results across wall assembly 1-4, we find that the percentage of OE savings per unit of EE spent as we approach assembly 4b (higher insulation level), is much lesser when compared with assembly 1b (less insulation).

Table 6 Summary of OE and EE variation, along with EE factor for wall assembly 3b, in a heating dominated region

MEASURES FOR OE REDUCTION	**ASSEMBLY 3b (U=0.036)**				
	OPERATING ENERGY	**EMBODIED ENERGY**	**DIFFERENCE**		
	EUI	**EE / AREA**	**% of OE DIFFERENCE**	**% of EE DIFFERENCE**	**EE factor EE/OE**
	kBtu / ft^2 /year	**kBtu / ft^2 /year**			
ASHRAE Benchmark (U=0.51)	80.436	8.155			
Most optimum	66.298	10.470	-17.577	28.393	0.158
ORIENTATION					
(-)90	77.192	8.339	-4.034	2.263	0.108
(-)45	77.562	8.339	-3.573	2.263	0.108
(+)180	79.243	8.339	-1.484	2.263	0.105
(+)90	77.044	8.339	-4.217	2.263	0.108
(+)45	78.621	8.339	-2.257	2.263	0.106
GLAZING					
Low-e	75.050	8.352	-6.696	2.425	0.111
Insulated reflective low-e	72.990	8.409	-9.257	3.124	0.115
2-pane low-e	72.347	8.420	-10.057	3.249	0.116
3-pane low-e	71.968	8.474	-10.528	3.922	0.118
SHADING					
1/6 window height	78.929	8.481	-1.874	4.002	0.107
1/4 window height	79.018	8.483	-1.763	4.024	0.107
1/3 window height	78.482	8.486	-2.430	4.064	0.108
1/2 window height	77.878	8.493	-3.180	4.146	0.109
2/3 window height	77.650	8.499	-3.464	4.226	0.109
WINDOW TO WALL RATIO					
15%	70.862	8.668	-11.902	6.293	0.122
30%	78.460	8.263	-2.457	1.328	0.105
40%	80.720	8.109	0.353	-0.555	0.100
50%	82.948	7.980	3.122	-2.136	0.096
ROOF CONSTRUCTION					
Q1	75.892	8.700	-5.650	6.685	0.115
Q2	75.809	8.872	-5.753	8.797	0.117
Q3	74.859	8.915	-6.934	9.330	0.119
Q4	74.759	10.328	-7.058	26.658	0.138

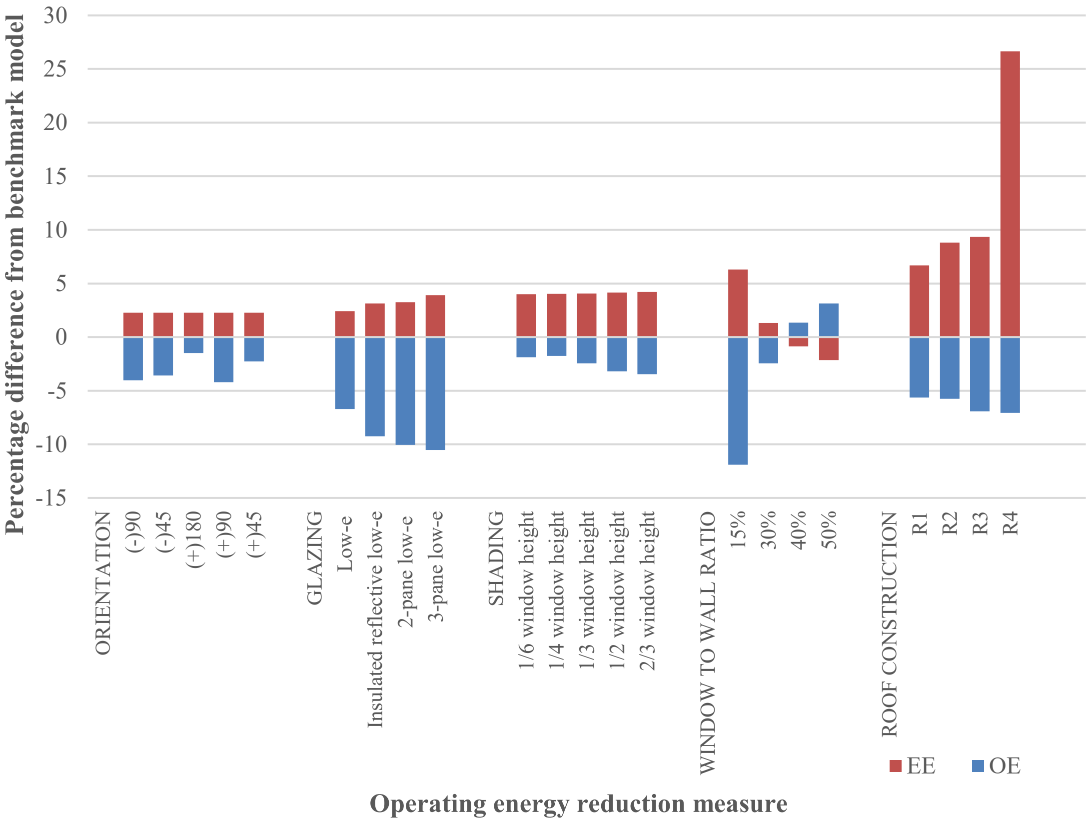


Figure 4 EE variation caused by applying OE reduction measures on Assembly 3b

The third OE reduction measure was to change the shading depth from 1/6 times the window height to 2/3 times the window height, for wall assembly 1b-4b. Amongst all the study cases for different wall assembly - that fall under the shade depth category, it was found that the shade depth of 1/6 times the window height had the highest EUI. For wall assembly 1b, saving approximately 1-2.5% of OE, results in spending 1.3-1.5% of EE (Table 4). For wall assembly 2b, we save around 1.5-3% of OE and spend 1.4-1.6% of EE (Table 5). For wall assembly 3b, OE reduction is calculated as 1.8-3.5%, while EE increase ranges between 3.5-4 % (Table 6). For wall assembly 4b, 3-5% of OE, results in spending 4.5 to 4.7 % of EE (Table 7). In terms of EUI, the most optimal window depth was found to be 2/3 times the window height, in all the study cases for wall assembly 1b-4b.

Table 7 Summary of OE and EE variation, along with EE factor for wall assembly 4b, in a heating dominated region

MEASURES FOR OE REDUCTION	ASSEMBLY 4b (U=0.033)				
	OPERATING ENERGY	EMBODIED ENERGY	DIFFERENCE		
	EUI	EE / AREA	% of OE DIFFERENCE	% of EE DIFFERENCE	EE factor EE/OE
	kBtu / ft^2/year	kBtu / ft^2/year			
ASHRAE Benchmark (U=0.51)	80.436	8.155			
Most optimum	66.170	10.520	-17.736	29.012	0.159
ORIENTATION					
(-)90	76.548	8.378	-4.834	2.740	0.109
(-)45	77.017	8.378	-4.251	2.740	0.109
(+)180	78.668	8.378	-2.199	2.740	0.106
(+)90	76.399	8.378	-5.019	2.740	0.110
(+)45	78.033	8.378	-2.988	2.740	0.107
GLAZING					
Low-e	74.467	8.391	-7.421	2.902	0.113
Insulated reflective low-e	72.260	8.450	-10.164	3.622	0.117
2-pane low-e	71.646	8.460	-10.929	3.744	0.118
3-pane low-e	71.225	8.513	-11.452	4.400	0.120
SHADING					
1/6 window height	78.464	8.520	-2.452	4.479	0.109
1/4 window height	78.367	8.523	-2.572	4.521	0.109
1/3 window height	77.818	8.527	-3.255	4.561	0.110
1/2 window height	77.158	8.532	-4.076	4.623	0.111
2/3 window height	76.835	8.538	-4.476	4.703	0.111
WINDOW TO WALL RATIO					
15%	71.330	8.604	-11.322	5.510	0.121
30%	78.966	8.208	-1.828	0.655	0.104
40%	81.126	8.056	0.858	-1.210	0.099
50%	83.260	7.976	3.511	-2.186	0.096
ROOF CONSTRUCTION					
Q1	75.291	8.714	-6.397	6.859	0.116
Q2	75.196	8.886	-6.515	8.972	0.118
Q3	74.254	8.930	-7.686	9.504	0.120
Q4	74.151	10.344	-7.814	26.852	0.140

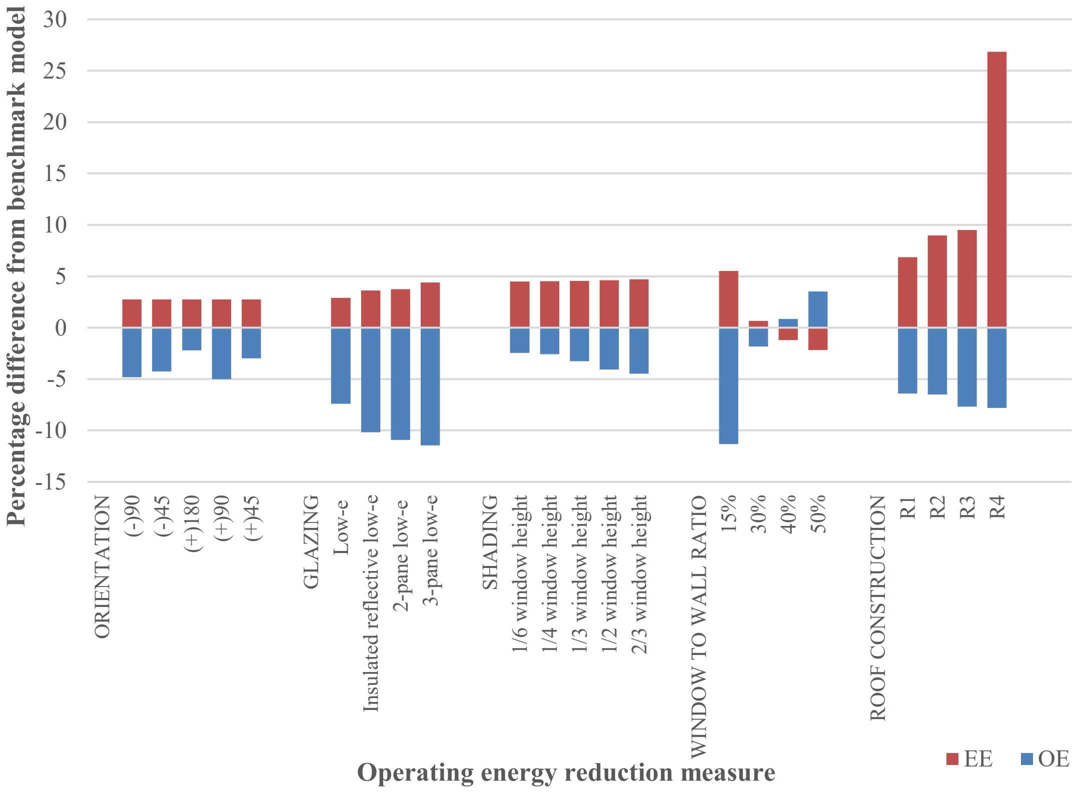


Figure 5 EE variation caused by applying OE reduction measures on Assembly 4b

The fourth OE reduction measure of changing the WWR from 15-50% was performed on wall assembly 1b-4b. For wall assembly 1b-4b changing the WWR to 15% causes approximately 11-12% decrease in OE, and nearly 5.5-6% increase in EE (as seen in Figures 2-4), while the WWR of 50% showed an increase in OE by 3.5% and decrease in EE demand by 2.13- 3%.

The final OE reduction measure, calculates the implications of changing the roof assembly Q1(R-30) to Q4 (R-45) on OE and EE components. For wall assembly 1b and

2b, it was found that decreasing OE by 5-7%, resulted in increasing EE by 4-24% (as seen in Figure 2). For wall assembly 3b, OE savings was calculated as 6-7%, while EE spent was between 7-27%. For wall assembly 4b, 6-8% decrease in OE resulted in increasing the EE by 7-27%. The overall results indicate that as we approach more insulated wall assemblies; there are lesser improvements to the EUI, while the embodied energy consumption increases.

To further investigate the impacts of OE reduction measures on EE, a combination of measures was applied on the baseline model to determine overall OE and EE implications. OE reduction measures that had the most impact under each category was manually selected from the matrix (Tables 4-7). These measures include, building orientation at (+90), 3-pane window glazing system, WWR of 15%, 36 in shade depth and Q4 (R-45) roof assembly. The subsequent impacts on the EE were observed. The simulated results show that the most optimized model created for wall assembly 1b, had an OE reduction of 17.1%, while the EE increased by 27.12% (Figure 6). Therefore, the EE factor for the most optimized version of wall assembly 1, was found to be 0.155. This implies that for every 1 kBtu increase in OE, 0.155kBtu of EE is expended. The most optimized version of wall assembly 2 showed an OE decrease of 17.43%, and an associated 27.21% increase in EE. The EE factor in this case was found to be 0.156. For wall assembly 3, decreasing the OE by 17.57%, resulted in increasing EE by 28.39%. The EE factor was found to be 0.157. For wall assembly 4, decreasing the OE by 17.73%, caused a 29.01% increase in EE. The EE factor is 0.158.

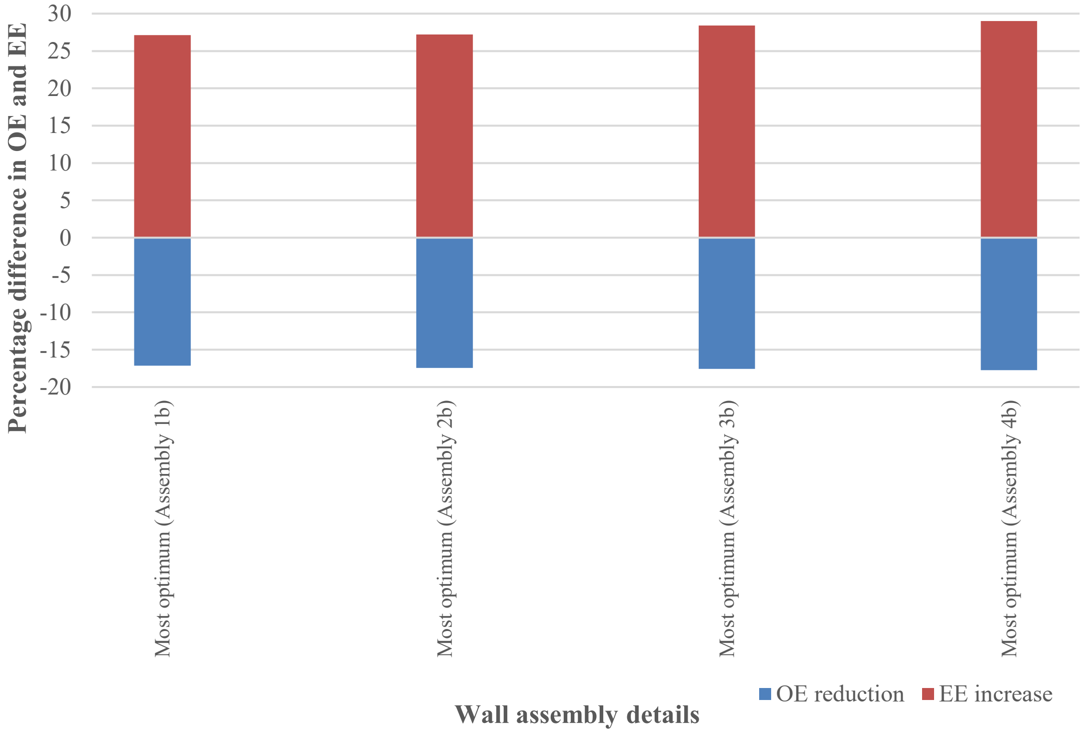


Figure 6 OE vs EE evaluation for the most optimized model across different wall assemblies (climate zone 5A)

The OE of a building can be further categorized into space heating loads, space cooling loads, and lighting loads. Figure 7 shows the energy trade-offs occur within OE components as well. For wall assembly 1b, changing the glazing system from low-e glass to 3-pane low-e glass or changing the shading depth from 9in to 36in results in decreasing the space cooling, while increasing space heating and lighting loads. Upon changing the WWR from 15% to 50% we observe the lighting load dramatically decreasing. This is attributed to the higher amounts of daylight entering the building. However, increasing the surface area of glass also results in increasing the space conditioning loads. Changing the level of insulation in the roof increases the cooling energy demand while decreasing the heating energy demand. This may be due to the increased level of insulation that results in trapping heat within the building for long time durations.

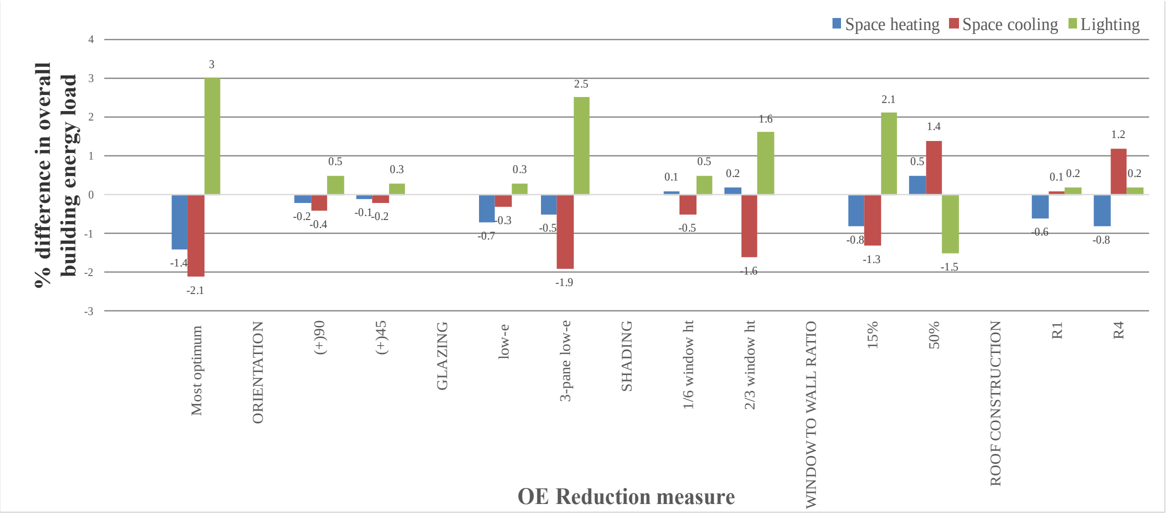


Figure 7 OE trade-offs for wall assembly 1b (climate zone 5A)

6.2. Cooling dominated region (climate zone 2A)

For climate zone 2A, we observed that the ASHRAE 90.1-2016, benchmark model has an EUI of 46.2 kBtu/ft^2/year, while the embodied energy consumption is 7.8 kBtu/ft^2/year (Tables 8-11). Overall, across the four assemblies the OE shows a reducing trend, while the EE shows an increasing trend (Figures 8-11).

Table 8 Summary of OE and EE variation, along with EE factor for wall assembly 1a, in a heating dominated region

MEASURES FOR OE REDUCTION	**ASSEMBLY 1a (U=0.066)**				
	OPERATING ENERGY	**EMBODIED ENERGY**	**DIFFERENCE**		
	EUI kBtu / ft² / year	**EE/Area kBtu / ft²/year**	**% of OE DIFFERENCE**	**% of EE DIFFERENCE**	**EE factor EE/OE**
ASHRAE Benchmark (U=0.075)	46.2	7.832			
Most optimum	39.5	9.910	-14.502	26.537	0.251
ORIENTATION					
(-)90	45.5	7.942	-1.515	1.410	0.175
(-)45	45.8	7.942	-0.866	1.410	0.173
(+)180	45.6	7.942	-1.299	1.410	0.174
(+)90	45.4	7.942	-1.732	1.410	0.175
(+)45	45.7	7.942	-1.082	1.410	0.174
GLAZING					
low-e	45.1	7.956	-2.381	1.591	0.176
Insulated reflective low-e	43.4	7.964	-6.061	1.693	0.184
2-pane low-e	43.2	8.023	-6.494	2.442	0.186
3-pane low-e	41.7	8.078	-9.740	3.150	0.194
SHADING					
1/6 window height	45	7.980	-2.597	1.896	0.177
1/3 window height	44.4	8.008	-3.896	2.252	0.180
1/4 window height	44.7	8.003	-3.247	2.185	0.179
1/2 window height	43.9	8.039	-4.978	2.641	0.183
2/3 window height	43.5	8.053	-5.844	2.822	0.185
WINDOW TO WALL RATIO					
15%	42.7	7.974	-7.576	1.817	0.187
30%	45.1	7.958	-2.381	1.608	0.176
40%	46.5	7.908	0.649	0.979	0.170
50%	48	7.891	3.896	0.757	0.164
ROOF CONSTRUCTION					
Q1	44.6	7.862	-3.463	0.385	0.176
Q2	44.2	7.965	-4.329	1.698	0.180
Q3	44.4	8.090	-3.896	3.304	0.182
Q4	43.9	9.455	-4.978	20.732	0.215

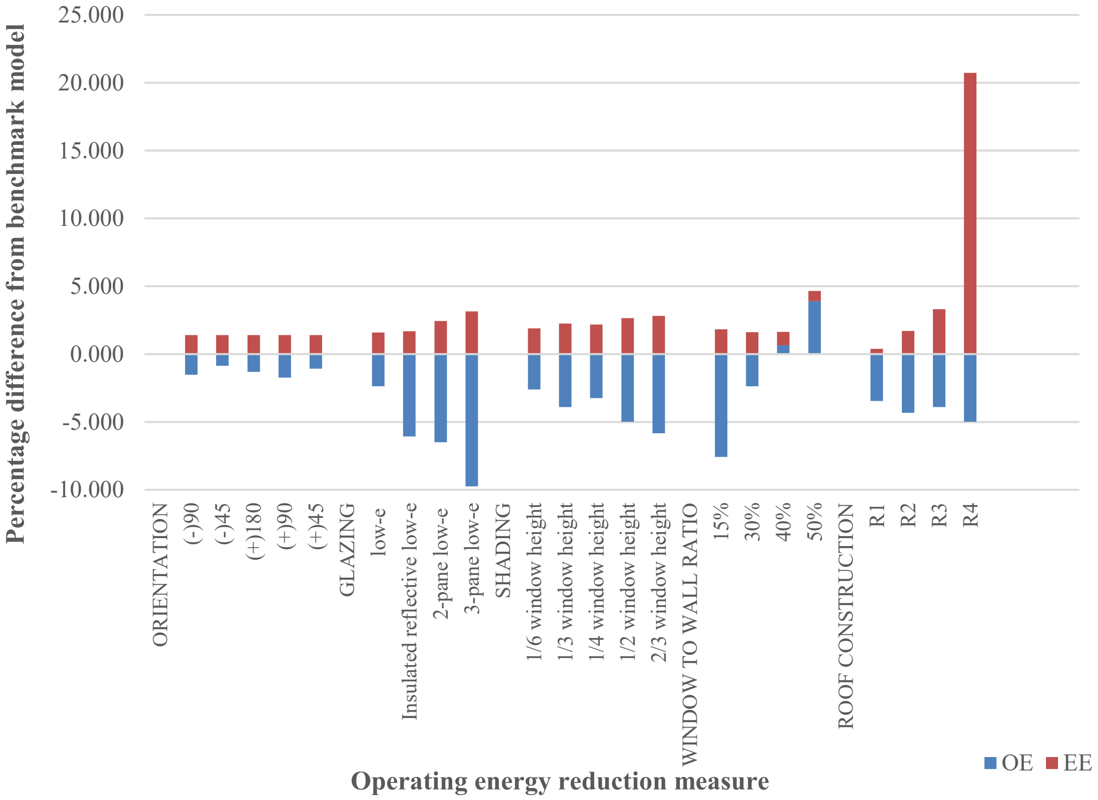


Figure 8 EE variation caused by applying OE reduction measures on Assembly 1a

For the first OE reduction strategy of changing the orientation, we found a similarity in the results between the two climate zones. Across the four assemblies, the model had the least energy consumption, when the project North was facing east. In both the cases (climate zone 2A and 5A), the EE does not show any variation since no additional material was added to the model.

Table 9 Summary of OE and EE variation, along with EE factor for wall assembly 2a, in a heating dominated region

MEASURES FOR OE REDUCTION	**ASSEMBLY 2a (U=0.052)**				
	OPERATING ENERGY	**EMBODIED ENERGY**	**DIFFERENCE**		
	EUI kBtu / ft^2 / year	**EE/Area kBtu / ft^2/year**	**% of OE DIFFERENCE**	**% of EE DIFFERENCE**	**EE factor EE/OE**
ASHRAE Benchmark (U=0.075)	46.200	7.832			
Most optimum	39.100	10.136	-15.368	29.428	0.259
ORIENTATION					
(-)90	45.100	8.086	-2.381	3.244	0.179
(-)45	45.400	8.086	-1.732	3.244	0.178
(+)180	45.200	8.086	-2.165	3.244	0.179
(+)90	45.400	8.086	-1.732	3.244	0.178
(+)45	45.300	8.086	-1.948	3.244	0.178
GLAZING					
low-e	44.900	8.100	-2.814	3.429	0.180
Insulated reflective low-e	43.100	8.104	-6.710	3.481	0.188
2-pane low-e	43.000	8.166	-6.926	4.268	0.190
3-pane low-e	41.300	8.376	-10.606	6.952	0.203
SHADING					
1/6 window height	44.700	8.094	-3.247	3.350	0.181
1/3 window height	44.000	8.100	-4.762	3.420	0.184
1/4 window height	44.500	8.097	-3.680	3.389	0.182
1/2 window height	43.700	8.108	-5.411	3.525	0.186
2/3 window height	43.200	8.115	-6.494	3.622	0.188
WINDOW TO WALL RATIO					
15%	42.500	8.431	-8.009	7.653	0.198
30%	44.900	8.086	-2.814	3.241	0.180
40%	46.300	7.934	0.216	1.305	0.171
50%	47.900	7.798	3.680	-0.428	0.163
ROOF CONSTRUCTION					
Q1	44.400	8.281	-3.896	5.740	0.187
Q2	43.900	8.367	-4.978	6.831	0.191
Q3	44.300	8.410	-4.113	7.379	0.190
Q4	43.700	9.623	-5.411	22.869	0.220

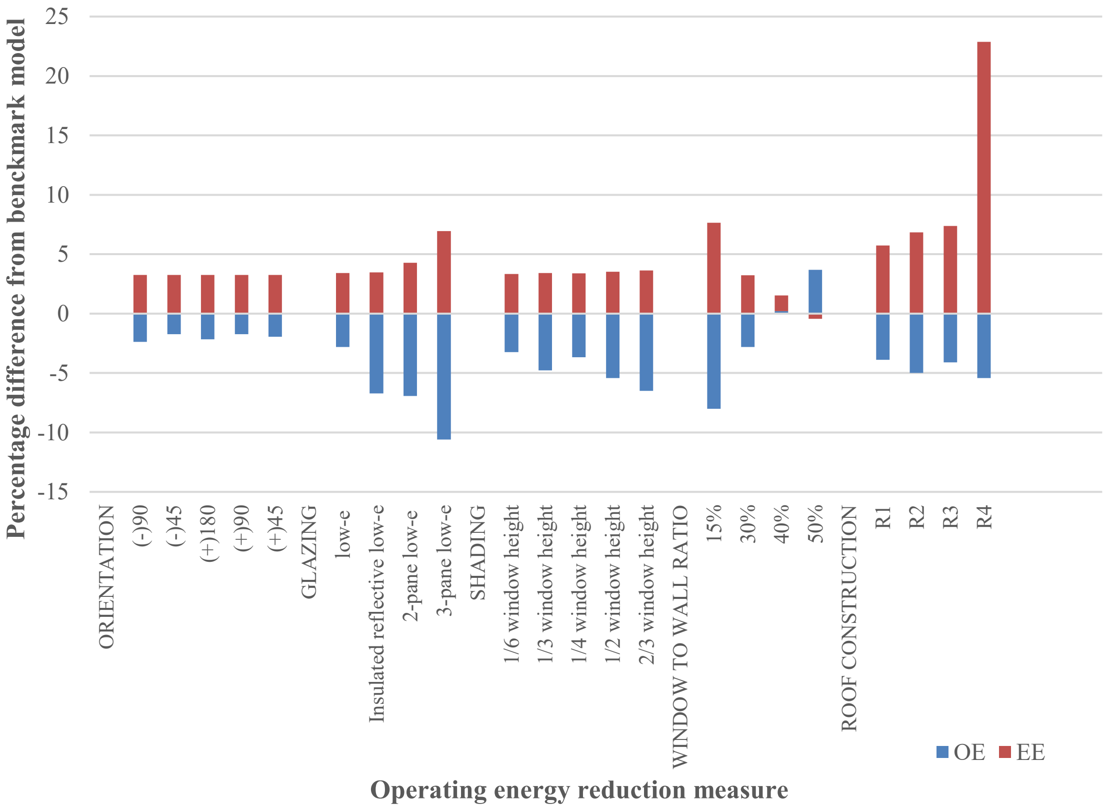


Figure 9 EE variation caused by applying OE reduction measures on Assembly 2a

For the second OE reduction measure of changing the glazing system used in the building. For wall assembly 1a, we found that OE decreased by 2.3-9.7%, while the EE increased by 1.6-3% (Table 8). For wall assembly 2a, saving 3-11% of OE, subsequently increased EE by 3.5-7.0% (Table 9). For wall assembly 3a, we calculated a 4-12% decrease in OE, while the EE increased by 4-6% (Table 10). For wall assembly 4a, a 4-12% decrease in OE, resulted in EE increase by 6-8% (Table 11).

Table 10 Summary of OE and EE variation, along with EE factor for wall assembly 3a, in a heating dominated region

MEASURES FOR OE REDUCTION	**ASSEMBLY 3a (U=0.047)**				
	OPERATING ENERGY	**EMBODIED ENERGY**	**DIFFERENCE**		
	EUI kBtu / ft² / year	**EE/Area kBtu / ft²/year**	**% of OE DIFFERENCE**	**% of EE DIFFERENCE**	**EE factor EE/OE**
ASHRAE Benchmark (U=0.075)	46.200	7.832			
Most optimum	38.400	10.186	-16.883	30.056	0.265
ORIENTATION					
(-)90	44.800	8.164	-3.030	4.246	0.182
(-)45	44.900	8.164	-2.814	4.246	0.182
(+)180	44.800	8.164	-3.030	4.246	0.182
(+)90	44.700	8.164	-3.247	4.246	0.183
(+)45	44.900	8.164	-2.814	4.246	0.182
GLAZING					
low-e	44.400	8.184	-3.896	4.500	0.184
Insulated reflective low-e	42.900	8.206	-7.143	4.785	0.191
2-pane low-e	42.600	8.217	-7.792	4.925	0.193
3-pane low-e	40.700	8.292	-11.905	5.878	0.204
SHADING					
1/6 window height	44.500	8.201	-3.680	4.715	0.184
1/3 window height	43.800	8.258	-5.195	5.444	0.189
1/4 window height	44.100	8.218	-4.545	4.927	0.186
1/2 window height	43.200	8.349	-6.494	6.605	0.193
2/3 window height	42.800	8.386	-7.359	7.077	0.196
WINDOW TO WALL RATIO					
15%	41.900	8.216	-9.307	4.908	0.196
30%	44.300	8.183	-4.113	4.484	0.185
40%	45.900	7.973	-0.649	1.803	0.174
50%	47.500	7.867	2.814	0.452	0.166
ROOF CONSTRUCTION					
Q1	44.100	8.321	-4.545	6.250	0.189
Q2	43.600	8.500	-4.762	8.527	0.195
Q3	44.000	8.552	-5.628	9.194	0.194
Q4	43.200	9.703	-6.494	23.888	0.225

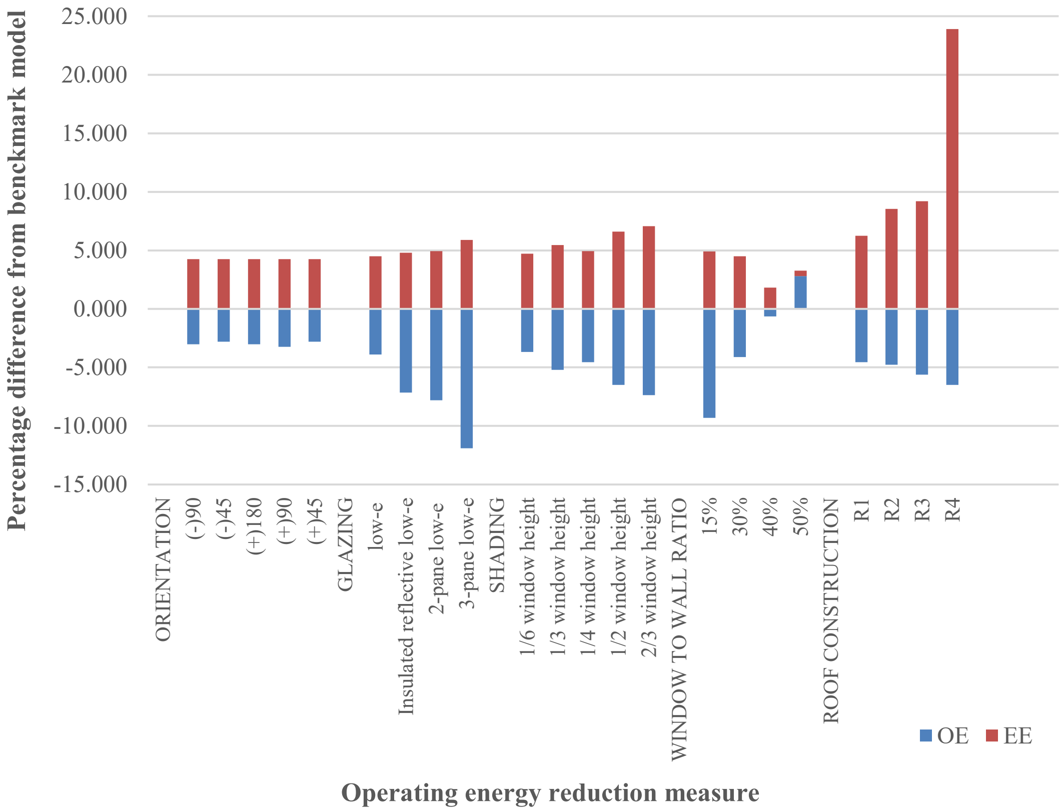


Figure 10 EE variation caused by applying OE reduction measures on Assembly 3a

Upon applying the third OE reduction measure of changing the shading depth, from 9 in to 36 in the following results were observed. For wall assembly 1a, 3-6% decrease in OE resulted in increasing EE by 2-3%. For wall assembly 2a, saving OE by 3-6% subsequently resulted in spending 3-4% of EE. For wall assembly 3a, we observe that OE reduces by 4-7% while EE increases by 5-7%. For wall assembly 4a, reducing OE by 5-8% increases EE by 7-8%.

Table 11 Summary of OE and EE variation, along with EE factor for wall assembly 4a, in a heating dominated region

MEASURES FOR OE REDUCTION	**ASSEMBLY 4a (U=0.037)**				
	OPERATING ENERGY	**EMBODIED ENERGY**	**DIFFERENCE**		
	EUI kBtu / ft^2 / year	**EE/Area kBtu / ft^2/year**	**% of OE DIFFERENCE**	**% of EE DIFFERENCE**	**EE factor EE/OE**
ASHRAE Benchmark (U=0.075)	46.200	7.832			
Most optimum	38.100	10.210	-17.532	30.367	0.268
ORIENTATION					
(-)90	44.600	8.290	-3.463	5.850	0.186
(-)45	44.800	8.290	-3.030	5.850	0.185
(+)180	44.700	8.290	-3.247	5.850	0.185
(+)90	44.600	8.290	-3.463	5.850	0.186
(+)45	44.700	8.290	-3.247	5.850	0.185
GLAZING					
low-e	44.200	8.339	-4.329	6.475	0.189
Insulated reflective low-e	42.600	8.348	-7.792	6.588	0.196
2-pane low-e	42.400	8.373	-8.225	6.911	0.197
3-pane low-e	40.500	8.484	-12.338	8.335	0.209
SHADING					
1/6 window height	44.100	8.342	-4.545	6.518	0.189
1/3 window height	43.500	8.351	-5.844	6.625	0.192
1/4 window height	43.800	8.346	-5.195	6.567	0.191
1/2 window height	43.000	8.478	-6.926	8.251	0.197
2/3 window height	42.600	8.495	-7.792	8.466	0.199
WINDOW TO WALL RATIO					
15%	41.400	8.612	-10.390	9.963	0.208
30%	44.100	8.285	-4.545	5.793	0.188
40%	45.700	8.167	-1.082	4.276	0.179
50%	47.300	8.054	2.381	2.837	0.170
ROOF CONSTRUCTION					
Q1	43.900	8.509	-4.978	8.645	0.194
Q2	43.800	8.713	-5.195	11.256	0.205
Q3	43.500	8.917	-5.844	13.862	0.199
Q4	43.300	9.928	-6.277	26.770	0.229

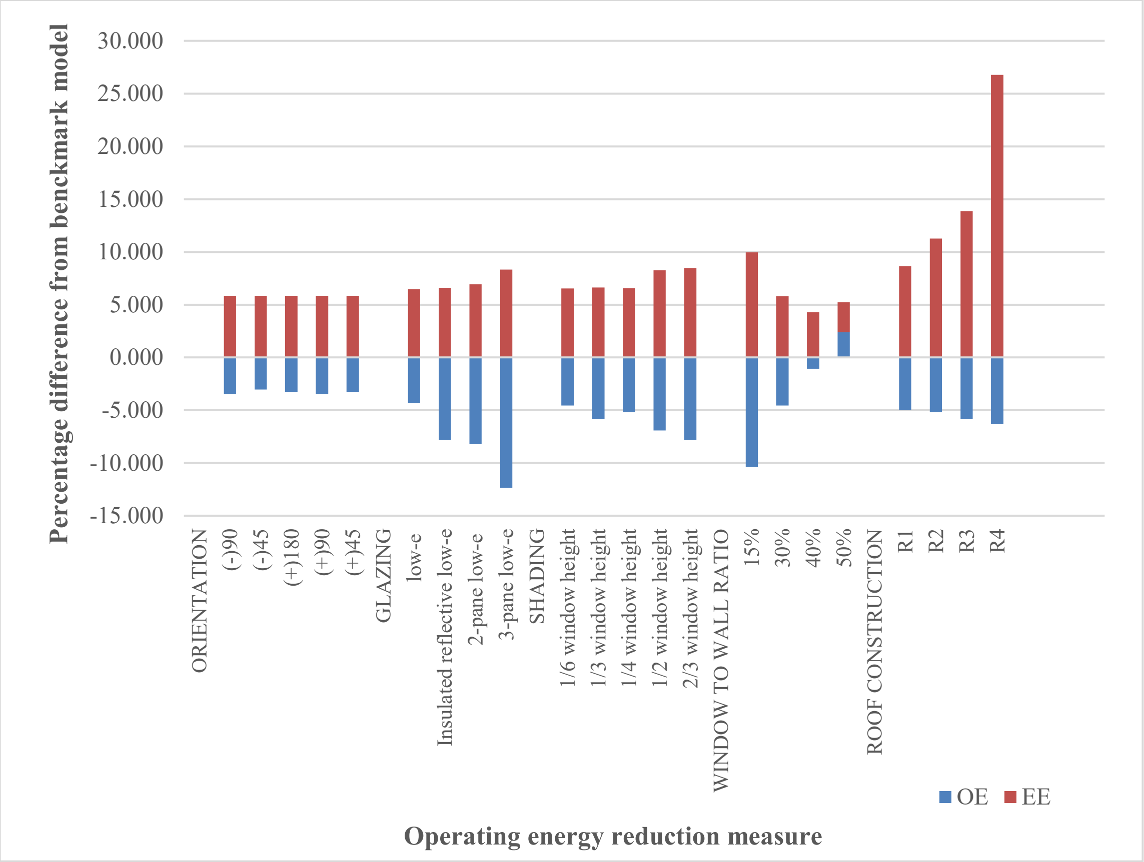


Figure 11 EE variation caused by applying OE reduction measures on Assembly 4a

Upon applying the final OE reduction measure of changing the insulation level (R-30 to R-45), the following implication were observed on the OE and EE components. For wall assembly 1a, decreasing 3-4% OE resulted in increasing 5-20% of EE. For wall assembly 2a, decreasing 3-5% OE, caused an increase of 6-23% in EE. For wall assembly 3a, decreasing 4.5-6 % OE, accounted for increasing 6-25% of EE. For wall assembly 4a, decreasing 5-6 % OE, increase EE by 8-26%. From the above results, we can conclude that changing the insulation levels in the roof has higher impact on the EE of a building when compared with OE.

To further emphasis upon the conflicting impacts of the OE reduction measures on EE. We created an optimized model using the process mentioned earlier in the study. For the hot-humid climate of Houston, we observed that for wall assembly 1a, reducing the OE by 14.5%, resulted in increasing the EE by 26.5%. For wall assembly 2a, reducing the OE by 15.3%, resulted in increasing the EE by 29.4%. For wall assembly 3a, reducing the OE by 16.8%, resulted in increasing the EE by 30.05%. For wall assembly 4a, reducing the OE by 17.5%, resulted in increasing the EE by 31.6%. The EE factor for the most optimized model varies from 0.25 to 0.26, across the different assemblies (Figure 12). These results show that improvements that are focused upon reducing operating energy are not sufficient to reduce overall building energy.

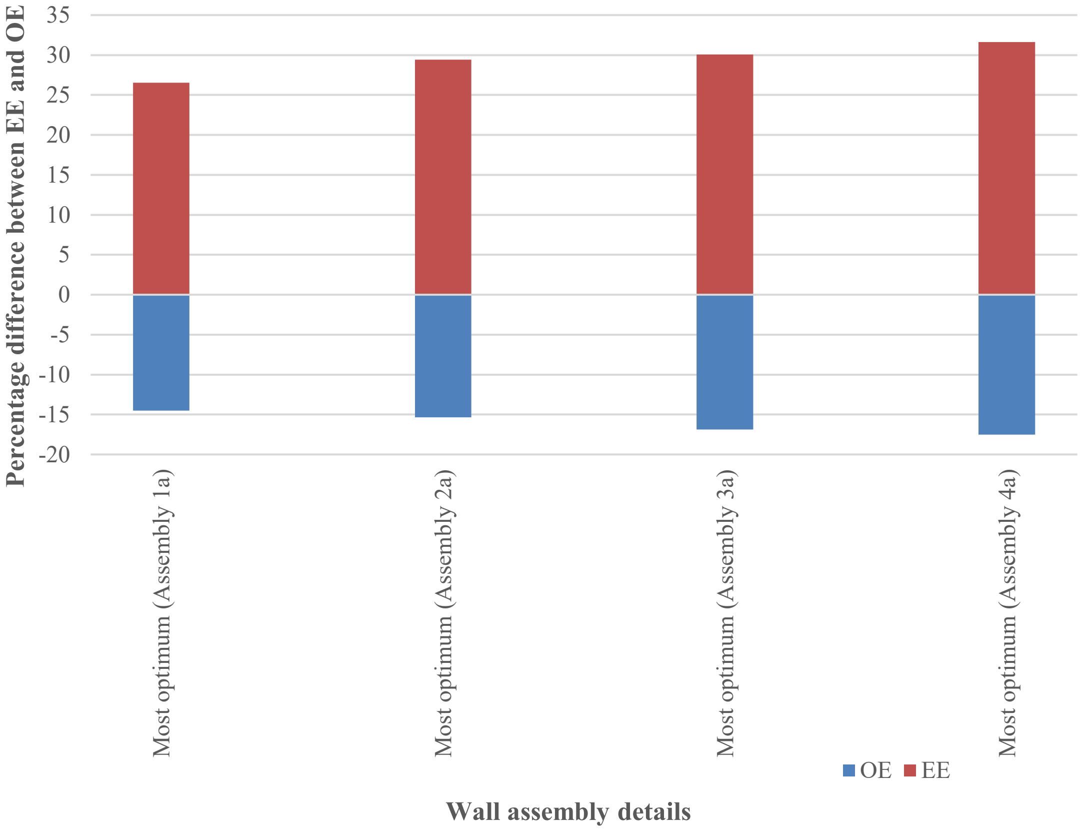


Figure 12 **OE vs EE evaluation for the most optimized model across different wall assemblies (climate zone 2A)**

For the hot-humid climate of Houston, we observe that for assembly 1a changing the glazing system or the level of shading does not have any impact on the space heating loads. In both the cases, the space cooling demand reduces while the lighting load increases. Changing the WWR from 15% to 50%, increases space cooling need while decreasing the lighting loads. Changing the level of insulation in the roofs reduced the cooling needs, while the lighting and heating requirements remained constant (Figure 13).

Figure 13 OE trade-offs for wall assembly 1a (climate zone 2A)

7. DISCUSSION

According to the literature review, we were able to identify five major clusters into which these OE reduction measures can be categorized. They were level of insulation (walls and roofs), building orientation, type of glazing system, depth of external shading, and window to wall ratio. For the typical ASHRAE 90.1, 2016 benchmark model, the application of these OE reduction measures shows different influences upon the overall building LCE.

Upon changing the orientation as an OE reduction measure it was found that the EUI decreases when the project north faces east (+90) in all our study cases. This implies that the longer building was aligned across the north-south direction. In addition, the EUI of the study cases across different construction assemblies showed very minor differences upon rotating the entire building by 180 degrees. This is because the baseline model is symmetrical over the building's central axis.

From the above calculations, changing the depth of the external shades, shows satisfactory benefits in terms of OE and EE demands. These benefits are evident from the gradient diagrams (Figure 2-5), since the negative values of OE and positive values of EE almost balance each other out. However, it is important to select the optimal overhang depth to obtain higher energy savings. Our study shows that the depth of the overhang directly correlates with the height of the window. This statement is further corroborated by the study conducted by Bellia et al. (2013) and Huang et al. (2012). Moreover, the functionality of the shades is used to its maximum potential only when they block the direct solar irradiance from hitting the glazing surface. In this regard of varying shade depths, the overall result obtained from our study is contradictory to the results obtained from the study performed by Huang et al. (2012). In their study, they found that LCE benefits from the use of external shading for a building located in Hong Kong, causes a negative impact, when it comes to EE consumption. This difference in results can be largely attributed to the difference in material used for the external shades and the climatic conditions of the studies.

The window to wall ratio has a significant impact on the overall energy consumption in a building. From our calculations, it was observed that reducing the WWR, increased the EE demand in the building. This is because the insulation material (XPS, EPS etc.) used in the wall assembly has much higher EE than that of glass. Thereby implying that the findings of our study are similar to the results found by Utama and Gheewala (2009). In addition, Yohanis and Norton (2002) found that a building that has a WWR of 15% has the least OE demand, which validates the findings of our study. Increasing the insulation thickness has positive implications on reducing the OE demand. However, our study observed that beyond a certain thickness, the insulation does not help with OE reduction. This is because greater levels of insulation increase the time lag, thereby trapping the heat that entered the building for long time durations. As a result, the cooling loads and EE loads of a building, eventually starts increasing. The findings of our study are supported by several other studies such as Rodrigues and Freire (2017), Utama and Gheewala (2009), and Radhi (2009).

The results obtained from our study show that the overall EE factor for the optimized model varies between 0.156-0.159 in climate zone 5A and 0.259-0.268 in climate zone 2A across construction assemblies. Thereby, indicating that the EE factor is much higher in climate zone 2A in comparison with climate zone 5A. Furthermore, we compared the results of our study with literature. Collinge et al. (2013) conducted a LCA of an institutional building (Benedum Hall, University of Pittsburgh) in the United states over a 75-year lifespan. The annual OE consumption in their study was found to be 345.175 kBtu/ft^2/year, this is much higher than the EUI we obtained in our study. This can be attributed to the additional loads (occupancy, plug, hot water) that was considered in the system boundary of their study. The EE demand is 5.9 kBtu/ ft^2/year resulting in an EE factor of 0.017. Scheuer et al. (2003) conducted a LCA of a six-storey building located in the University of Michigan campus for a 75-year life span of the building. The annual OE consumption was 361.025 kBtu/ft^2/year and EE consumption was 7.3 kBtu/ft^2/year. Thereby, resulting in an EE factor of 0.020. The study by Junnila et al. (2006) conducted a LCA on a five-storey office building in the Midwest region of the United States. The annual OE consumption was 119.754 kBtu/ft^2/year, while the EE was 13.9 kBtu/ft^2/year. In this case, we calculated the EE factor as 0.116. The variation in results across the studies might be due to the difference in the type of material used, construction method, climatic zone and system boundary considered in each case. This makes it difficult to compare the results obtained from our study with existing literature.

In addition, the study faced several challenges to run energy simulation using a BIM enhanced approach. The previously suggested workflow of extracting material information from Autodesk Revit into GBS had issues of interoperability, since the U-values of all the materials were not exported accurately. While certain U-values of the materials used in a particular construction assembly were as per the required specification; the specification of certain materials were not replicated as required. In this case, default U-values of the materials were used from the GBS library. To resolve this issue, we used pre-populated lists of construction assembly data, that was readily available in GBS to generate results for our study cases. The whole process became extremely time-consuming, since the results of GBS had to be verified using another energy simulation tool called e-Quest. As seen in Figure 14 and 15, the variation in the results generated from e-quest and GBS for wall assembly 1a and 4a were similar. The models were not calibrated to show similar EUI, since we were only concerned with their absolute differences.

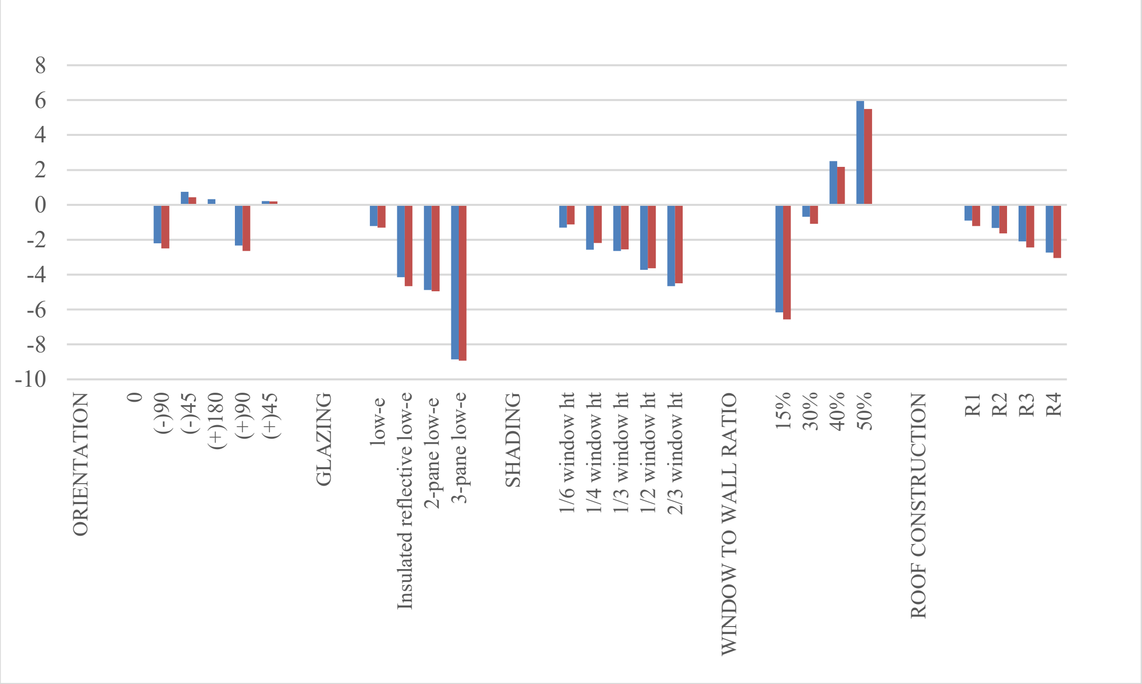


Figure 14 e-Quest vs GBS, variation in EUI, for wall assembly 1a

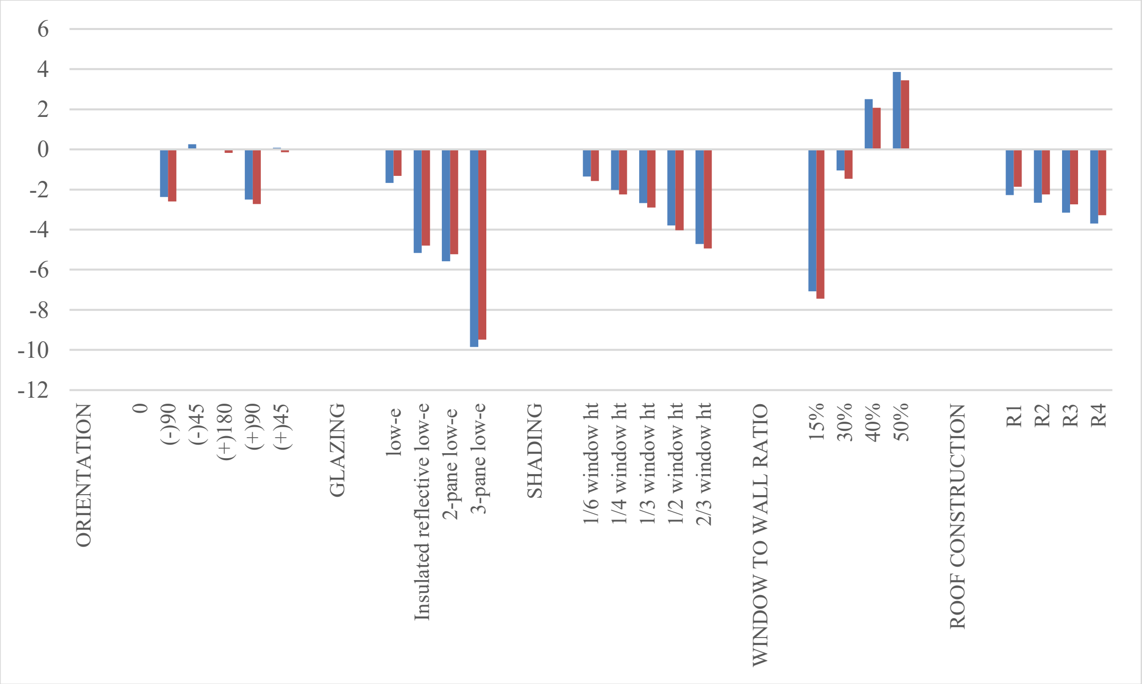


Figure 15 e-Quest vs GBS, variation in EUI, for wall assembly 4a

The EE results that we obtained from Tally was not verified using another software, since EE calculation is much more complex when compared with OE calculations (Dixit, 2017). Moreover, there are several methods of calculating EE such as, process-based method, input-out based and hybrid methods. Each of these methods also use different sources of data and system boundaries (Dixit, 2017). For instance, Tally uses the GaBi database that is dynamically updated on the cloud based on current industry standards while Athena IE uses a custom database that is embedded within the software (the user does not have access to view the values used in EE calculation). Another reason for discrepancy of results between the two software is the method of quantity take-off. To check the accuracy of data extraction between the two software (Tally and Athena IE), the quantity take-offs were exported as excel spreadsheets. Upon comparing the data in the spreadsheets, several differences were observed between the two interfaces. This may be attributed to the difference in the level of detail extracted from Autodesk Revit model to Tally when compared with the Athena IE software (Schultz et al., 2016).

8. CONCLUSIONS

This study has investigated the lifecycle energy implications of using operating energy reduction measures in commercial buildings. The extensive review of literature helped us establish a base for our study, by providing us with information regarding the various clusters of OE reduction strategies that are currently used in the building industry. This information helped us generate clusters, of study cases, that would be essential in identifying building energy trade-offs. The study has demonstrated, using a BIM enhanced approach, that simply changing the type of glazing, level of insulation (in the walls or roofs), the depth of external shades, and WWR to reduce OE demand might result in paradoxically increasing overall LCE, due to the use of additional energy-intensive material. Therefore, causing a detrimental implication on our final goal of reducing energy consumption. This study shows that design decisions need to carefully analyze and address the trade-offs from a holistic lifecycle energy perspective, that includes both EE and OE components.

The results obtained from our study show that the overall EE factor for the optimized model varies between 0.156-0.159 in climate zone 5A and 0.259-0.268 in climate zone 2A across construction assemblies. Thereby, indicating that the EE factor is influenced by the climate of a region. Conducting similar case studies, with the same system boundary in different climatic zones will help in establishing a range of values for the EE factor in each climate zone.

Furthermore, it is important to mention that this study was conducted under various limitations. This study conducted energy simulations based upon the five broad categories, the impact of changing the glass type for the skylights and varying floor assemblies were not analyzed. The results of the study are also restricted to a specific building type, form, geographic location and climate (variations might yield different results). The study accounted only the building envelope loads (i.e. occupancy and plug loads were not considered). In addition, the study did not address the change in OE demand over the 60-year lifecycle of the building. Certain inaccuracies are existent in this study, due to issues of interoperability between Autodesk Revit and Green Building Studio. Moreover, different software platforms were used to compute EE and OE requirements of the building.

An assessment of the EE implications caused by OE reducing measures, will allow decision makers to take an informed step towards reducing overall energy consumption in buildings, by taking into account the relevance of the choice of construction materials and assemblies. The results obtained from this study would assist building designers and energy consultants take much informed decisions regarding the optimization measures they choose to implement in their building design. In future, this knowledge can be used to develop a genetic algorithm that can optimize overall building LCE, based on conflicting LCE components by conducting parametric simulations.

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APPENDIX A

WALL ASSEMBLY DETAILS

ASHRAE PRESCRIPTIVE CODE FOR WALLS IN CLIMATE ZONE 2A WALL: **Umax assembly = 0.089; Insulation Rmin=13** ROOF**: Umax assembly = 0.039; Insulation Rmin=25**				**ASHRAE PRESCRIPTIVE CODE FOR WALLS IN CLIMATE ZONE 5A** WALL: **Umax assembly = 0.055; Insulation Rmin=13+10 c.i.** ROOF: **Umax assembly = 0.032; Insulation Rmin=30**			
ASHRAE 90.1-2016 benchmark				**ASHRAE 90.1-2016 benchmark**			
Wall: U=.075	**R-value/inch**	**thickness (in)**	**R-value**	**Wall: U=.051**	**R-value/inch**	**thickness (in)**	**R-value**
Exterior Air film	0.17	1	0.17	Exterior Air film	0.17	1	0.17
Stucco	0.2	4	0.8	Stucco	0.2	4	0.8
Sheathing	0.56	5/8"	0.56	Sheathing	0.56	5/8"	0.56
Effective framing for R-13	1.714	3.5	6	Effective framing for R-13	1.714	3.5	6
Fiberglass Batt	3	1.5	4.5	Fiberglass Batt	3	3.5	10.5
Drywall/ gypsum board	0.56	5/8"	0.56	Drywall/ gypsum board	0.56	5/8"	0.56
Interior Air film	0.68	1	0.68	Interior Air film	0.68	1	0.68
TOTAL			13.27	TOTAL			19.27
Wall assembly 1a				**Wall assembly 1b**			
Wall: U=.066	**R-value/inch**	**thickness (in)**	**R-value**	**Wall: U=.04**	**R-value/inch**	**thickness (in)**	**R-value**
Exterior Air film	0.17	1	0.17	Exterior Air film	0.17	1	0.17
Brick	0.2	4	0.8	Brick	0.2	4	0.8
Sheathing	0.56	5/8"	0.56	Sheathing	0.56	5/8"	0.56
Effective framing for R-13	1.714	3.5	6	Effective framing for R-13	1.714	3.5	6
Mineral wool	3.12	2	6.24	Cellulose Insulation	4	4	16
Drywall/ gypsum board-	0.56	5/8"	0.56	Drywall/ gypsum board	0.56	5/8"	0.56
Interior Air film	0.68	1	0.68	Interior Air film	0.68	1	0.68
TOTAL			**15.01**	TOTAL			24.77
Wall assembly 2a				**Wall assembly 2b**			
Wall: U=.052	**R-value/inch**	**thickness (in)**	**R-value**	**Wall: U=.039**	**R-value/inch**	**thickness (in)**	**R-value**
Exterior Air film	0.17	1	0.17	Exterior Air film	0.17	1	0.17
Concrete panels	0.08	2	0.16	Brick	0.2	4	0.8
Sheathing	0.56	5/8"	0.56	Sheathing	0.56	5/8"	0.56
Effective framing for R-13	1.714	3.5	6	Effective framing for R-13	1.714	3.5	6
Mineral wool	3.12	3.5	10.92	Extruded polystyrene	5.5	3	16.5
Drywall/ gypsum board	0.56	5/8"	0.56	Drywall/ gypsum board	0.56	5/8"	0.56
Interior Air film	0.68	1	0.68	Interior Air film	0.68	1	0.68
TOTAL			19.05	TOTAL			25.27
Wall assembly 3a				**Wall assembly 3b**			
Wall: U=.047	**R-value/inch**	**thickness (in)**	**R-value**	**Wall: U=.036**	**R-value/inch**	**thickness (in)**	**R-value**
Exterior Air film	0.17	1	0.17	Exterior Air film	0.17	1	0.17
Concrete panels	0.08	2	0.16	Stone veneer (limestone)	0.114	4	0.456
Sheathing	0.56	5/8"	0.56	Sheathing	0.56	5/8"	0.56
Effective framing for R-13	1.714	3.5	6	Effective framing for R-13	1.714	3.5	6
Expanded polystyrene	3.7	3.5	12.95	Extruded polystyrene	5.5	3.5	19.25
Drywall/ gypsum board	0.56	5/8"	0.56	Drywall/ gypsum board	0.56	5/8"	0.56
Interior Air film	0.68	1	0.68	Interior Air film	0.68	1	0.68
TOTAL			21.08	TOTAL			27.676

Wall assembly 4a				**Wall assembly 4b**			
Wall: U=.037	**R-value/inch**	**thickness (in)**	**R-value**	**Wall: U=.033**	**R-value/inch**	**thickness (in)**	**R-value**
Exterior Air film	0.17	1	0.17	Exterior Air film	0.17	1	0.17
Stone veneer (limestone)	0.114	4	0.456	Stone veneer (limestone)	0.114	4	0.456
Sheathing	0.56	5/8"	0.56	Sheathing	0.56	5/8"	0.56
Effective framing for R-13	1.714	3.5	6	Effective framing for R-13	1.714	3.5	6
High density fiberglass batt	3.6	3.5	12.6	High density fiberglass batt	3.55	3.5	12.425
Polyurethane insulation	6	1	6	Polyurethane insulation	6.1	1.5	9.15
Drywall/ gypsum board-	0.56	5/8"	0.56	Drywall/ gypsum board	0.56	5/8"	0.56
Interior Air film	0.68	1	0.68	Interior Air film	0.68	1	0.68
TOTAL			27.026	TOTAL			30.001

APPENDIX B

ROOF ASSEMBLY DETAILS

ASHRAE PRESCRIPTIVE CODE FOR ROOFS IN CLIMATE ZONE 2A and 5A

ROOF: Umax assembly = 0.039; Insulation Rmin=25

ROOF: Umax assembly = 0.032; Insulation Rmin=30

Roof assembly Q1				**Roof assembly Q3**			
Roof: U=.034	**R-value/inch**	**thickness (in)**	**R-value**	**Roof: U=.031**	**R-value/inch**	**thickness (in)**	**R-value**
Exterior Air film	0.17	1	0.17	Exterior Air film	0.17	1	0.17
Roofing membrane				Roofing membrane			
Roof board	0.45	5/8"	0.45	Roof board	0.45	5/8"	0.45
EPS insulation	3.95	7	27.65	Rigid foam insulation	5.51	5.5	30.30
Sheathing	0.45	5/8"	0.45	Sheathing	0.45	5/8"	0.45
Vapor barrier				Vapor barrier			
Steel deck	0	0	0	Steel deck	0	0	0
Interior Air film	0.68	1	0.68	Interior Air film	0.68	1	0.68
TOTAL		9	29.4	**TOTAL**		7.5	32.055
Roof assembly Q2				**Roof assembly Q4**			
Roof: U=.0331	**R-value/inch**	**thickness (in)**	**R-value**	**Roof: U=.022**	**R-value/inch**	**thickness (in)**	**R-value**
Exterior Air film	0.17	1	0.17	Exterior Air film	0.17	1	0.17
Roofing tiles	0.44	2	0.88	Roofing tiles	0.44	2	0.88
Roofing membrane				Roof board	0.45	5/8"	0.45
Roof board	0.45	5/8"	0.45	Fiberglass batt insulation	3.2	1	3.2
XPS insulation	5.5	5	27.5	Polyurethane board	6.6	6	39.6
Sheathing	0.45	5/8"	0.45	Sheathing	0.45	5/8"	0.45
Vapor barrier				Vapor barrier			
Steel deck	0	0	0	Steel deck	0	0	0
Interior Air film	0.68	1	0.68	Interior Air film	0.68	1	0.68
TOTAL		9	30.13	TOTAL		11	45.43