IMPACT ASSESSMENT OF ENERGY CONSERVATION MEASURES ON BUILDING ENERGY CONSUMPTION, CARBON EMISSION, AND ADAPTATION COST USING FUTURE WEATHER DATA

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ABSTRACT

The sixth Intergovernmental Panel on Climate Change assessment report shows a 1.5˚ Celsius increase in the earth's temperature by 2040 which could lead to catastrophic weather events. Keeping this projection to the lower range through mitigation efforts is therefore of paramount importance. Buildings account for a significant amount of carbon emissions. Therefore, predicting buildings' energy consumption and carbon emission in advance and implementing the most cost and energy-efficient strategies accordingly can help to combat climate change. This paper analyzed the energy consumption and carbon emission of an office building in 16 US climate zones now and in 2050 using future weather data. Also, the impact of three energy conservation measures and their implementation cost has been assessed in the cities with higher future energy use to suggest the most energy and cost-effective building upgrade that can offset the additional energy consumption caused by global warming with a reasonable payback period.

Keywords: climate change, energy conservation measure, upgrade cost, payback period.

1 INTRODUCTION

The potential threat of global warming to the ecosystem and human living conditions has been a major source of public concern over the past decade. IPCC has projected an increase in annual temperature that ranges from 1 to 7 Kelvin from 1960s to 2100s (IPCC, 2021). These changes will result in increased building energy loads, operational energy use, and carbon emissions. With the increased worldwide concern about climate change, the construction industry is also grappling with the topic of how expected climatic shifts will affect the performance of buildings all around the world. To address this concern, structures and systems constructed today must be designed to lower greenhouse gas emissions (GHGs) in both current and future climate scenarios, reducing the burden GHGs impose on present and future generations.

The first step to achieve this goal is to understand the future climate conditions under different climate change scenarios as defined by the IPCC report, and their impact on building energy consumption and carbon emissions in different climate regions. During the past years, research has been conducted to explore several workflows utilized for building energy use prediction like- generating synthetic building energy model (BEM) datasets using computational methods (Vaidhyanathan, 2021) or create reliable weather files for building energy use prediction. One of the common methods to generate future weather data is morphing, which adjusts a current weather file by using projections from either Regional Climate Models (RCM) or General Circulation Models (GCM). However, one of the limitations of this method is that it depends on the current baseline weather data, and does not consider all aspects of future climate change. Our study uses the CCworldWeatherGen tool which utilizes the Hadley Centre Coupled Model Version 3 (HadCM3) climate model to generate the future weather files (CCWorldWeatherGen, 2021). HadCM3 is a coupled climate model that has been developed in 1999 and is extensively used for climate prediction (Met Office Climate Prediction Model, 2021).

Based on various methods of future weather prediction, most of the previous research studies suggest a decrease in heating requirements in cold climates and an increase in cooling requirements in hot and tropical regions around the globe (Olonscheck et al., 2011). A study of climate change and heat island impact in 25 locations across the globe by Crawley suggests a 10% decrease in annual energy consumption in cold climates, and a 20% increase in energy consumption in tropical climates (Crawley, 2008). The increase in energy consumption results in increased carbon emissions. Therefore, acquiring the future end-use energy and carbon emission data helps to find the best building upgrade options to counteract the increase in energy consumption in future climate conditions. Wan et al. assessed the impact of three energy conservation measures (ECM) on building energy reduction for five cities in China, and concluded that the lighting load reduction is the most effective strategy in office buildings. (Wan et al., 2012) Rubio-Bellido et al. evaluated the impact of Window-to-Wall ratio (WWR) on energy demand in Chile and concluded that solely changing the WWR would be insufficient to remove the extra future energy use (Rubio-Bellido et al., 2016). However, combining efficient lighting systems with an optimized WWR can significantly lower building energy use in all climate zones (Zolfaghari & Jones, 2022). Karimpour et al. studied the impact of various ECMs on residential buildings in Australia and concluded that high-performance insulation, especially for roofs, is crucial in reducing the future building energy consumption (Karimpour et al., 2015). Nassif et al. studied the impact of HVAC system interventions on buildings' energy use and suggested energy savings ranging from 1.6% to 5.7% by improving the operation of the VAV component (Nassif, et al., 2022)(Talib et al., 2019). Many other researchers studied the impact of other ECMs in various locations around the world and yielded results that are highly different based on the climate, building type, and location (Pérez-Andreu et al., 2018)(Zarrabi et al., 2019). These findings facilitate the adoption of energy-saving measures for different building types, in different climate regions. They also provide guidelines for future energy code adjustment and moving towards more stringent energy codes which smooth the way for achieving net-zero energy in buildings (Pease et al., 2021).

While there are many studies assessing the impact of climate change on building energy consumption and the effect of various ECMs on lowering the possible increase in future energy use, there is a gap in studying the cost implications of applying these ECMs and how it compares to future operational energy cost. Assessing different future energy cost scenarios and comparing them with the building upgrade cost helps with evaluating the payback period and feasibility of the building upgrade decisions for each location. This study tries to fill this gap by assessing the impact of climate change on building energy consumption and carbon emission in 2050 in 16 locations representing each of the U.S. climate zones. Further, to limit the impact of climate change on building energy consumption and maintain the current building energy consumption in 2050, the energy savings and cost implications of three common energy conservation methods are examined against present and predicted future energy demands to introduce the most impactful ones, with a reasonable payback period in each climate region.

2 METHODOLOGY

This study used a computer simulation method to simulate the energy use difference of a medium office operating today and in the year 2050, in 16 cities each representing one ASHRAE climate zone. EnergyPlus TMY3 weather files have been used to obtain the energy consumption results in the current climate condition. EPW files representing future weather conditions were created using the CCWorldWeatherGenerator tool, and future Design Days used for systems auto-sizing were generated using the future weather files.

By comparing the Energy Use Intensity (EUI) of the office building in the current and future climate in each city, the locations which face an increase in energy consumption in the future are then selected for taking the analysis forward. In the next step, three common ECMs were defined and applied to the medium office in each location to simulate the impact of each and find the most efficient one for each climate zone. Metrics such as cooling and heating load, source and site energy, source, and site EUI, end-use summary including lighting and equipment, and total electricity and natural gas energy were extracted from the report summary for further assessment. Figure 1 puts forward an overview of the methodology and steps that were taken to achieve the results and generate the metrics.

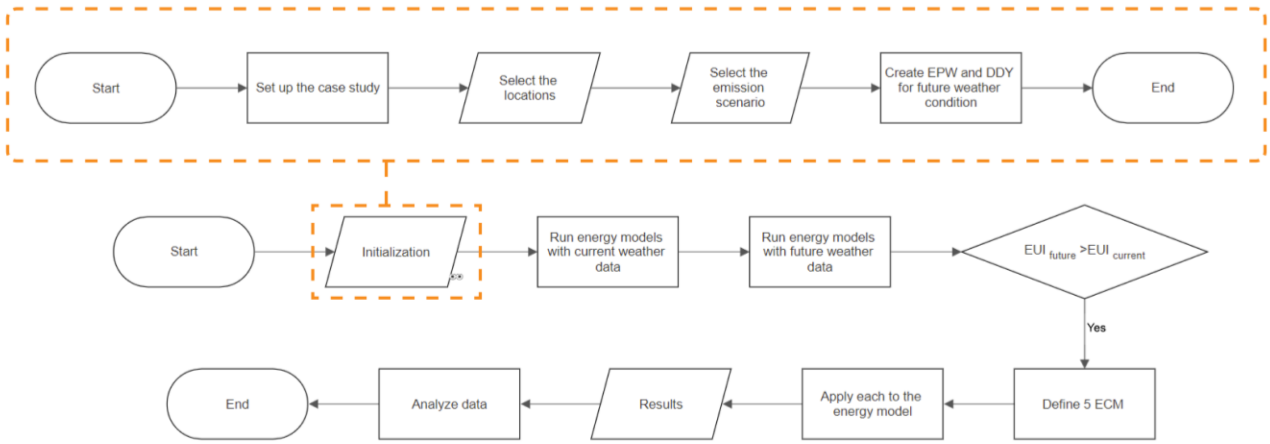


Figure 1: Flowchart of Study Steps.

2.1 Case Study

The Pacific Northwest National Laboratory (PNNL) Prototype building for medium office shown in table 1(oriented north-south) has been selected as the case study. However, some of the building characteristics such as envelope thermal properties, heating efficiency, cooling efficiency, etc. have been adjusted to the code minimum requirements suggested by different versions of ASHRAE Standard 90.1 adopted by each city and state (American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2022). Table 2 shows the list of cities referenced by the DOE along with the energy codes adopted by each location.

Table 1: Building Characteristics

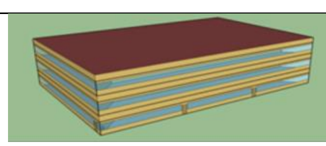
Total Floor Area (sqft)	Building Shape	# of Foors	WWR	Window Location
53,600 (163.2 *109.2)		3	35%	Evenly Distributed along 4 Facades
Shading Geometry	Azimuth	Floor to Floor Height (ft)	Floor to Ceiling Height (ft)	Glazing Sill Height (ft)
None	Non-directional	13	9	3.35

Table 2: List of Cities, Climate Zones, and Energy Codes

City	Climate Zone	Energy Code	City	Climate Zone	Energy Code
Miami	1A	2016	Albuquerque	4B	2016
Houston	2A	2013	Seattle	4C	2018 WSEC
Phoenix	2B	2013	Chicago	5A	2016
Atlanta	3A	2013	Boulder	5B	2016
Los Angeles	3B-Coast	Title 24	Minneapolis	6A	2016
Las Vegas	3B	2016	Helena	6B	2010
San Francisco	3C	Title 24	Duluth	7	2013
Baltimore	4A	2013	Fairbanks	8	2016

2.2 Weather files

Typical Meteorological Year version 3 (TMY3) weather files derived from the DOE dataset were used to run the energy models in the current climate (EnergyPlus, 2022). Future weather files are generated by CCWorldWeatherGen which uses a morphing methodology to create new EPW files transformed from original EPW data initially inserted into the tool. Note that this tool utilizes model summary data from the HadCM3 A2 experiment ensemble from the IPCC Fourth Assessment Report, which is accessible through the IPCC Data Distribution Centre (IPCC DDC). The A2 scenario is a high emission scenario, but not the highest as described in the Special Report on Emissions Scenarios (SRES).

2.3 Simulation engine

A simulation method using cove.tool and OpenStudio applications was utilized to predict the current and future energy consumption (Cove.Tool, 2021). The geometry was created inside cove.tool using a built-in 3D modeling feature. For each city, the TMY3 weather data along with all the ASHRAE 90.1 code minimum values (for various code versions) were automatically assigned to the project after entering the location when creating each project. In the next step, an osm file with all the project geometry, envelope, room, and system data was generated via the loadmodeling.tool feature. This osm file was then used for whole-building energy simulation and was fed into Parametric Analysis Tool (PAT) as a seed model to parametrically analyze the impact of ECM options by utilizing OpenStudio measures.

2.4 Energy conservation measure

Energy Conservation measures are building upgrades or modifications that can improve the energy efficiency of existing buildings and reduce the operational cost and carbon emission overall. This study uses three common energy conservation measures (table 3) to find the best-suited building upgrade to offset the increased energy use in the PNNL medium office building in each location. ECMs are limited to the building envelope and lighting system improvements. The level of improvement is different in each city as the goal is to keep the future energy consumption close to its current values. See Table 5 for intervention details for each ECM in each city.

Table 3: List of Energy Conservation Measures (ECM)

ECM	Description
ECM 1	Window SHGC and U value Reduction
ECM 2	Exterior wall and Roof insulation increase
ECM 3	Daylight Sensors + LPD reduction

3 COST ASSUMPTIONS:

The costs of building upgrades for different Energy Conservation Measures are determined by creating separate cost estimates per ECM per city using the RS Means (Robert Snow Means Company, 1942) estimating platform (RSMeans Green Building Cost Data, 2022). The methodology for selecting assemblies and products to be used in the estimates is segmented into three steps. First, the assemblies and products are chosen based on the requirement set by the PNNL building type (see Table 4). Second, the climate zone for each city is considered when selecting assemblies and products. Third, using the 2022 RS Means Cost Database, cost items are selected per city using the standard union rate and include material, equipment, labor, general overhead, and profit costs (Table 5). RS Means data is updated at large on an annual basis and incrementally every quarter, as a compilation of cost data generated from the construction industry in North America.

Table 4: Detail of assemblies used for each ECM calculation

Stucco Exterior Assembly	**Built-Up Roofing**	**Exterior Glazing**	**Lighting and Occupancy Sensors**
▫ Stucco, 3 coats, float finish, with mesh, on wood frame, 7/8" thick ▫ Partition, galvanized LB studs, 18 ga x 4" W studs 16" OC x 10' H, incl galvanized top & bottom track, excl openings, headers, beams, bracing & bridging ▫ Metal lath, diamond, expanded, galvanized, 2.5 lb./S.Y. ▫ Elastomeric sheet waterproofing, polyvinyl chloride sheets, plain, 20 mils thick ▫ Weather barriers, building paper, spun bonded polyethylene ▫ Wall insulation, rigid, fiberglass, unfaced, 3" thick, R13, 3#/CF ▫ Wall insulation, rigid, fiberglass, unfaced, 1-1/2" thick, R6.5, 3#/CF ▫ Gypsum wallboard, on walls, standard, taped & finished (level 4 finish), 5/8" thick	▫ SBS modified bituminous membrane, granule surface cap sheet, polyester reinforced, 120 to 149 mils, mopped ▫ Roof deck insulation, install perlite insulation, 2-1/2" thick R30, fastening excluded ▫ Roof deck insulation, polyisocyanurate, 3-1/2" thick, 2#/CF density, fastening excluded ▫ Roof deck insulation, polyisocyanurate, tapered for drainage, fastening excluded ▫ Metal roof decking, steel, open type B wide rib, galvanized, over 500 Sq, 1-1/2" D, 22 gauge	▫ Aluminum frame, window wall, mill finish, 2" x 4-1/2" deep, insulating glass	▫ Recess mounted in ceiling, 2.4 watts per S.F., 60 FC, 15 fixtures @ 32 watts per 1,000 S.F. ▫ Lighting devices, occupancy sensors, dual technology, ceiling mounted

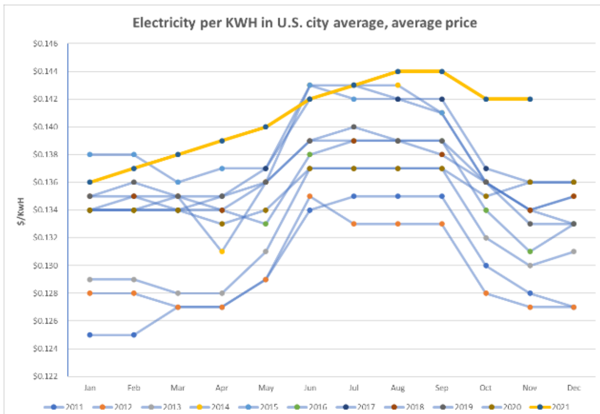
Table 5: Quantities and Unit Cost inputs for each ECM

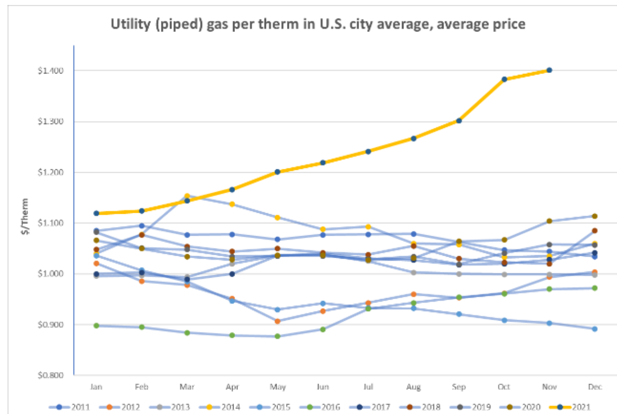
Climate Zone	**Energy Conservation Measure**	**Assembly Description**	**Quantity**	**Unit**	**Unit Cost**
1A – Miami, FL	ECM 1: 15% Reduction in window U-value & SHGC	Aluminum frame, window wall with insulating glass, U-0.4, SHGC 0.2	7027	SF	$118.10

	ECM 2: 40% increase in roof and ext. wall R-value	Built Up roofing, R30 insulation + Stucco Exterior with R20 insulation	53628	SF	$9.79
	ECM 3: Sensors + LPD reduction by 5%	Ceiling mounted dual tech sensors + Linear lighting fixture, 2.4W/SF	53628	SF	$6.23
2A – Houston, TX	ECM 1: 20% Reduction in window U-value & SHGC	Aluminum frame, window wall with insulating glass, U-0.2, SHGC 0.2	7027	SF	$116.59
	ECM 2: 40% increase in roof and ext. wall R-value	Built Up roofing, R30 insulation + Stucco Exterior with R20 insulation	53628	SF	$8.97
	ECM 3: Sensors + LPD reduction by 5%	Ceiling mounted dual tech sensors + Linear lighting fixture, 2.4W/SF	53628	SF	$5.71
2B – Phoenix, AZ	ECM 1: 10% Reduction in window U-value & SHGC	Aluminum frame, window wall with insulating glass, U-0.3, SHGC 0.2	7027	SF	$117.76
	ECM 2: 30% increase in roof and ext. wall R-value	Built Up roofing, R25 insulation + Stucco Exterior with R18 insulation	53628	SF	$9.69
	ECM 3: Sensors + LPD reduction by 5%	Ceiling mounted dual tech sensors + Linear lighting fixture, 2.4W/SF	53628	SF	$5.83
3A – Atlanta, GA	ECM 1: 20% Reduction in window U-value & SHGC	Aluminum frame, window wall with insulating glass, U-0.2, SHGC 0.2	7027	SF	$118.58
	ECM 2: 50% increase in roof and ext. wall R-value	Built Up roofing, R35 insulation + Stucco Exterior with R28 insulation	53628	SF	$9.70
	ECM 3: Sensors + LPD reduction by 5%	Ceiling mounted dual tech sensors + Linear lighting fixture, 2.4W/SF	53628	SF	$6.25
3B – Las Vegas, NV	ECM 1: 10% Reduction in window U-value & SHGC	Aluminum frame, window wall with insulating glass, U-0.3, SHGC 0.2	7027	SF	$128.75
	ECM 2: 40% increase in roof and ext. wall R-value	Built Up roofing, R30 insulation + Stucco Exterior with R20 insulation	53628	SF	$12.94
	ECM 3: Sensors + LPD reduction by 10%	Ceiling mounted dual tech sensors + Linear lighting fixture, 2.2W/SF	53628	SF	$7.85

At the time that this study is conducted (2022), the building construction sector is amid recovery from the COVID-19 pandemic as well as external world events that put energy sourcing at an unprecedented level of uncertainty. According to the Bureau of Labour Statistics (BLS), Consumer Price Index (CPI) in 2022 rose to 7.5% over one year, with core inflation averaging at 3.5% from 2021-2022 (Bureau of Labor Statistics, 2021). For this reason, the cost estimates are escalated to the year 2050 using an annual escalation rate of 3.5% per annum, which depicts an assumed "business as usual" circumstance where there is minimal change in terms of policy and external worldly events in the future.

In the last 10 years, electricity rates have averaged at $0.14/kWh in the average U.S. city while natural gas rates have averaged at $1.04/therm, according to BLS data (Figures 2, 3).





Figures 2: Historical Electricity Rates from 2011-2021   Figure 3: Natural Gas Rates from 2011-2021

Electricity rates remained steady with minimal change from year to year, with rates remaining at an average of $0.13-$0.14/kWh. Meanwhile, natural gas rates show to be more volatile, with annual average rates as low as $0.92-$1.23/therm. Based on this historical data, the determination of future electricity and natural gas rates are derived by applying an annual inflation rate of 0.78% and 1.08%, respectively, resulting in a rate of $0.17/kWh and $1.66/therm. Nevertheless, it is worth noting that as electrification, particularly electrification using renewable sources, continues to progress, the cost of electricity may remain stagnant or even potentially decrease in the future.

The cost estimate for each ECM is further analyzed to assess the payback years. In the context of this study, payback years is defined as the amount of time it takes for the investment to equal the energy cost savings. The formula used for the simple payback calculation is as follows:

Payback Years = Investment ($) / (Baseline Annual Utility Cost – ECM Annual Utility Cost)

4 RESULTS

4.1 Baseline models

After running 32 baseline energy models for 16 locations with current and projected 2050 weather files, the results show that among all the cities, only Miami-FL (1A), Houston-TX (2A), Phoenix-AZ (2B), Atlanta-GA (3A), and Las Vegas-NV (3B) will have a higher energy consumption in future mainly due to an increase in the cooling load. The energy consumption in Albuquerque, Minneapolis, and Los Angeles will stay close to current levels. The remaining locations will see a slight decrease in site energy.

An increase in temperature and humidity is excepted for Climate zones 1 to 4 which are considered hot-humid to mixed-humid. However, the results indicate that the energy use in cities representing climate zone 3C, 4A, 4B, and 4C will decrease or remain unchanged. The results agree with a study by Barbero et al. which predicted days with high wet-bulb temperature in the US between 2040-2060 in case of a high emission scenario (Barbero et al., 2015). Based on this study, climate change does not follow a pattern based on the current climate zones but is more specific to the geography of the regions. The highest impact occurs in some parts of the Mid-West, South, and North-East. The results of the above research verify that the results attained for counties representing climate zone 3C, 4A, 4B, and 4C are reasonable as they are located outside of the extreme weather areas.

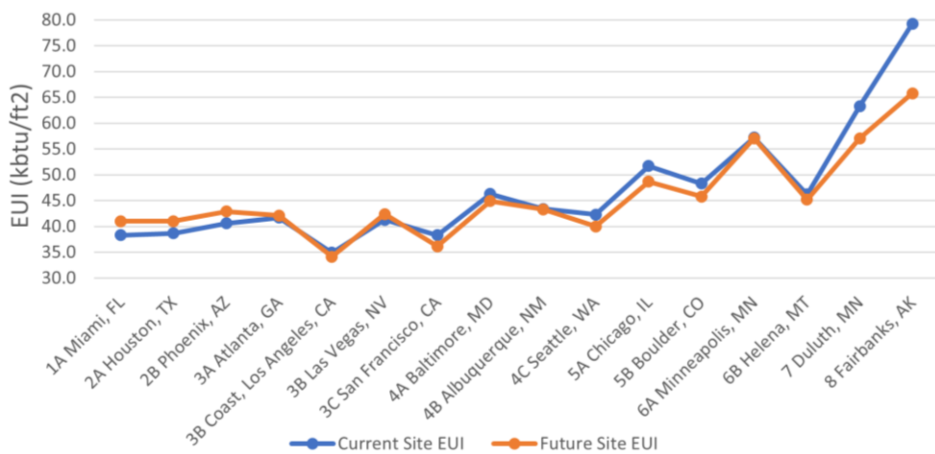


Figure 4: Future Site EUI vs Current Site EUI

4.2 Electricity and Natural Gas

Figure 5 compares the current and future electricity and natural gas usage in various locations. with assuming the current energy source trend continues in the future, the results indicate that due to the decrease in heating load and the increase in cooling load because of global warming, natural gas usage will be lower while electricity usage will be higher in future climate conditions compared to now.

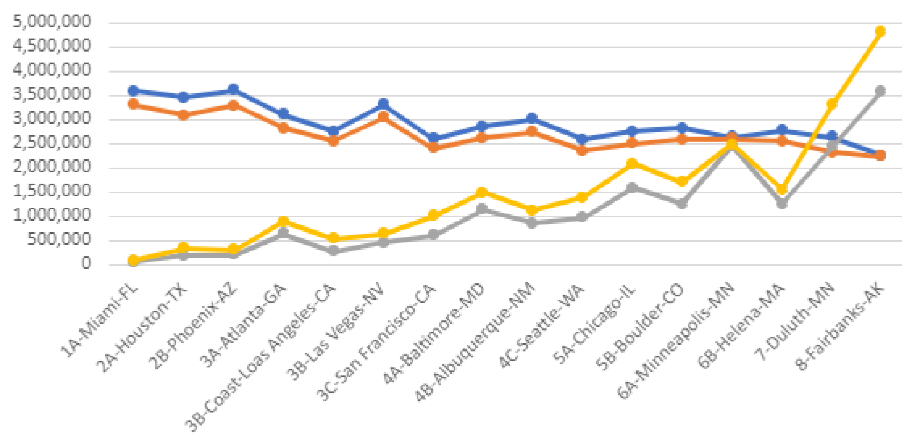


Figure 5: Future and Current Natural Gas and Electricity Use

4.3 Source EUI

Figure 6 compares the current and future source EUI in each location. The site-to-source conversion factor is 3.167 for electricity and 1.084 for natural gas based on the EnergyPlus report. As shown in the figure, the source EUI will increase in the future climate condition for all the locations except for Fairbanks. The differences between current and future source energy are higher in warmer climate zones. According to figure 5, there will be an increase in electricity consumption and a decrease in natural gas consumption in 2050. Since the site-to-source conversion factor for electricity is nearly three times that of natural gas, and the electricity usage is higher in the future, the overall source energy of the building will be higher in 2050 (Energy Star, 2022).

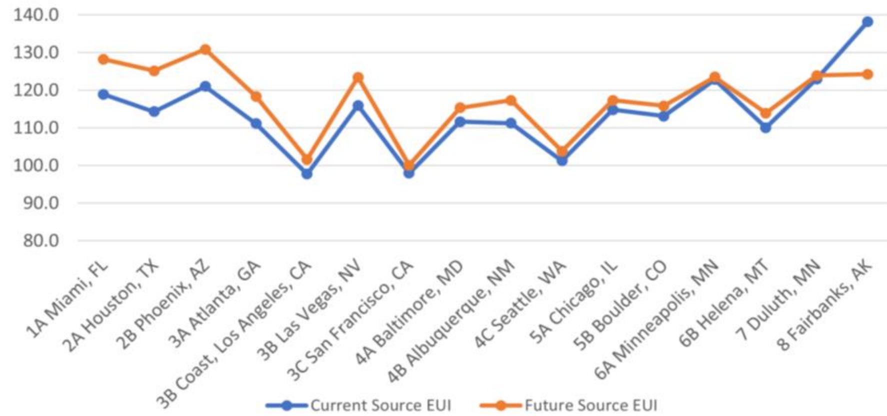


Figure 6: Future Source EUI vs Current Source EUI

4.4 Energy Conservation Measures

After predicting the future energy use, three common ECMs were tested in 5 cities with higher future energy use to find the most impactful one to offset the additional energy caused by the increase in temperature. ECM 1 represents a decrease in windows' SHGC and U value; ECM 2 represents an increase in exterior walls and roofs' insulation, and ECM 3 represents an upgrade to luminaires and adding daylight sensors (See Table 5). Figure 7 shows the percentage increase or decrease of the values for each ECM per location to offset the extra amount of cooling load based on future climate conditions. The results suggest:

- ECM 3 requires the slightest upgrade (ranging from 5% to 10%) to maintain the current energy consumption in the future. Adding daylight sensors combined with a 5% reduction in lighting power density (LPD) helps to maintain the current energy use or reach a lower energy consumption in 2050 in all the locations except for Las Vegas which requires a 10% reduction.
- Increasing the insulation of exterior walls and roofs requires the highest upgrade ranging from 30% to 55%. Atlanta requires the largest and Phoenix requires the slightest improvement in insulation.
- Between 10% to 20% reduction in window U value and SHGC will offset the extra cooling load in future climate conditions for all the locations.

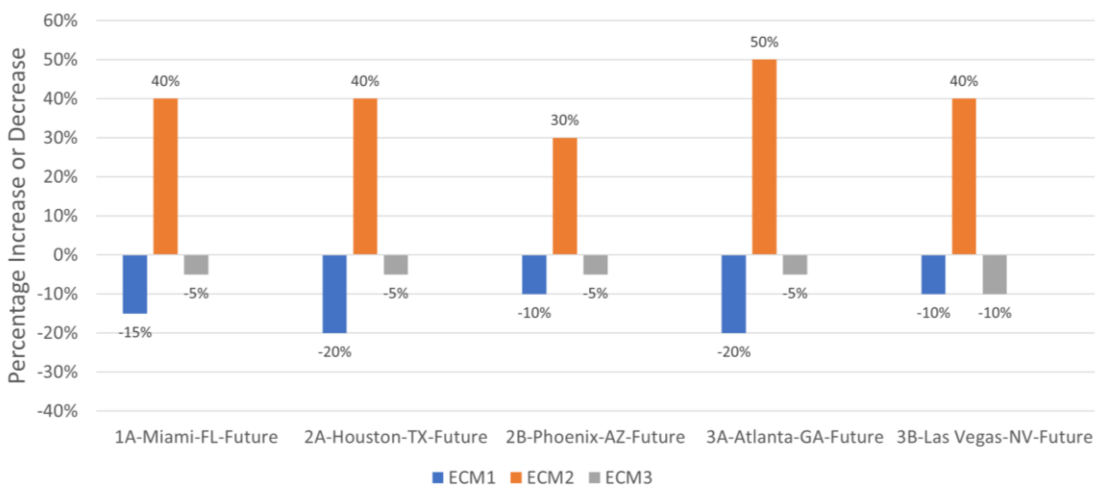


Figure 7: Level of Intervention per ECM

Figure 8 shows the future EUI after applying the ECMs against the building's EUI in the current climate condition. Based on the results, the most impactful ECM in all locations is adding daylight sensors and using more efficient luminaires. While this strategy has a minor impact on the building's peak cooling load, it significantly reduces the lighting load over the entire year and results in much less energy consumption.

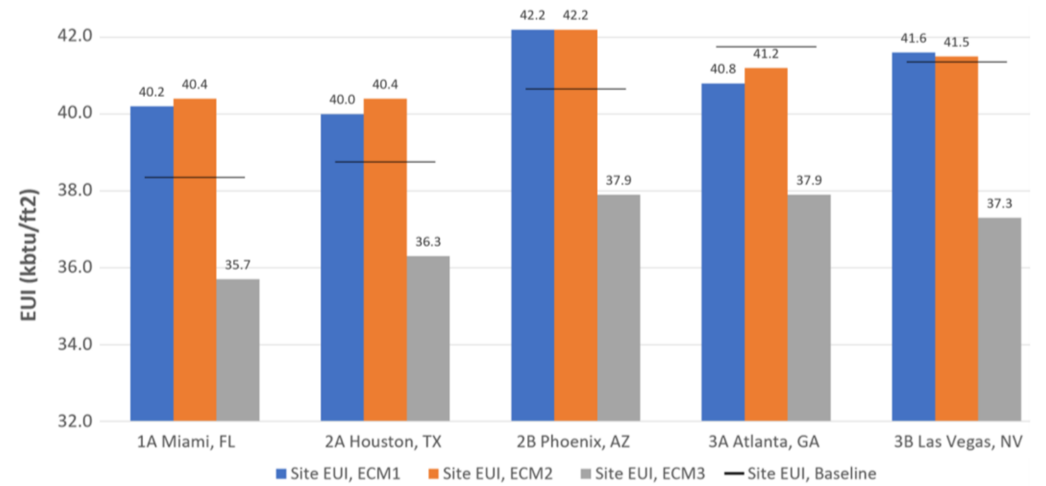


Figure 8: Baseline and Future Site EUI Comparison Per ECM

4.5 Operational Carbon Emission

The formula below was used to calculate the operational carbon emission. Carbon factors for each state were sourced from the EPA eGrid database and a constant natural gas (181 gCO2 e/kwh) factor was sourced from the EIA database (*Emissions & Generation Resource Integrated Database (EGRID) | US EPA*, 2022) (*U.S. Energy Information Administration (EIA)*, 2022). The carbon factor unit is gCO2e/kWh and the carbon emission unit is Tonne CO2e/yr. Due to uncertainty about changes to future carbon factors, the current average values were used for future carbon emission prediction.

Carbon emission = (total_electric * co2_factor + total_gas * 181)/ 1000000

According to figure 9, future carbon emissions are slightly higher in most locations and no link between carbon emission and climate zone can be found. This is due to the local differences in emission factors which are determined based on the source, solar, gas, coal, etc., and the efficiency of local electrical power production plants and transmission networks.

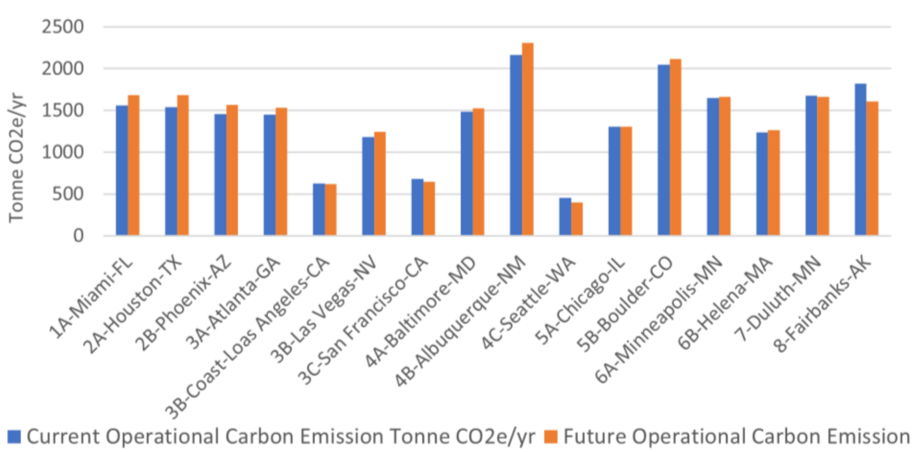


Figure 9: Future vs Current Carbon Emission

4.6 Cost Results

After calculating the cost of initial investments for each ECM and payback years, the following results can be determined (also shown in Figure 10):

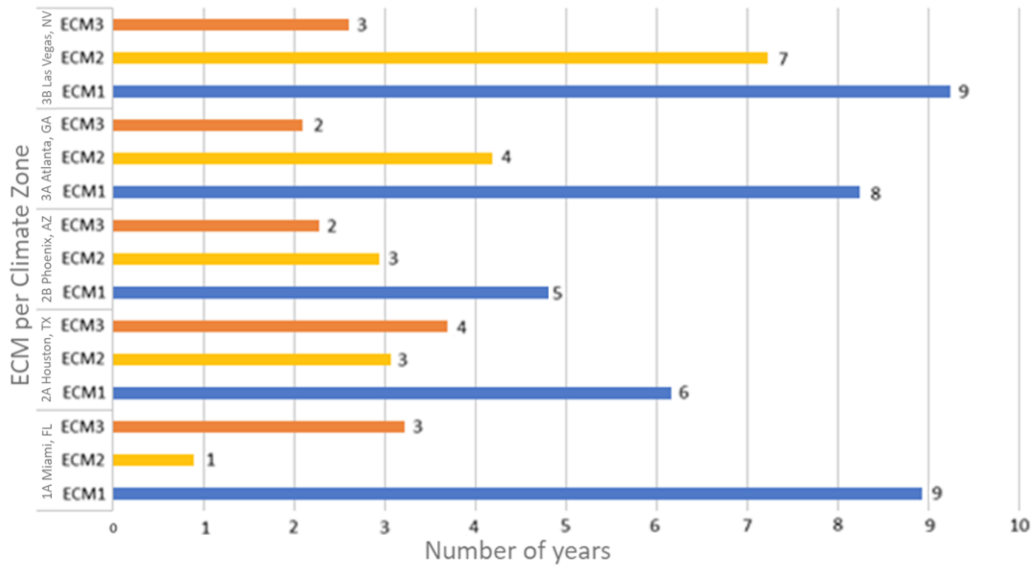


Figure 10: Payback Years of each ECM

- For Miami and Houston, ECM 2, which increases the R-values of roof and wall assemblies, yielded the least amount of payback years. For these locations, the investment cost for ECM 2 is the median investment cost.
- For Phoenix, Atlanta, and Las Vegas, ECM 3, which introduces sensors as well as reduces lighting power density, yielded the least amount of payback years. For these locations, ECM 3 also yields the lowest upgrade investment cost.
- For all climate zones, ECM 3 is shown to have the lowest cost of investment.

5 CONCLUSION AND FUTURE WORK

This study assesses the impact of climate change on energy consumption and carbon emissions of a medium office in 16 cities representing each of the U.S. climate zones. Further, the impact of three energy conservation measures (ECMs) along with their cost of implementation, has been assessed in the cities with higher future energy use intensity. This is used to suggest the most energy-efficient and cost-effective building upgrade, that can offset the additional energy consumption caused due to global warming with a reasonable payback period. The results provide the decision-makers with a building upgrade guide for different climate zones and energy code pairs, that can be used to neutralize the impact of climate change in 2050 with minimum cost implications. It also provides insights on changes that can be applied to the energy codes to enforce lower energy consumption and carbon emission from the construction sector.

This research contains various limitations. The study assessed the impact of global warming under the A2 scenario, while it is better to consider other emissions scenarios as well for a more holistic assessment. The future weather files are created based on the historic weather data (TMY2) and using other weather sources can result in different future predictions. Therefore, there is always uncertainty when using any of these weather file generator tools. Also, present-day carbon factors are used to calculate the operational carbon emissions in 2050 due to uncertainty about the future grid emissions. The future electricity rate does not take into account any further cost premium, which can result from widespread electrification implementation. Furthermore, additional ECMs could be evaluated in additional locations and for other building types.

Future work will focus on addressing and incorporating the above mentioned limitations of the current study. That being said, it will also take into consideration extreme weather events, passive survivability, and study of the upgrade cost for other ECMs under various emission scenarios considering different plots for utility cost based on different policies and predictions.

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