HEALTH IMPACTS ASSOCIATED TO BUILDING ENERGY CONSUMPTION AND POTENTIAL RESPONSE STRATEGIES

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Abstract

Climate change impacts our health directly and indirectly and is essential to develop response measures which would enhance a sustainable design and provide health co-benefits. Buildings are major consumers of fossil fuels and their direct contribution to global warming is well understood. In 2017, approximately 40% of the total energy consumption in the U.S. was consumed by the residential and commercial sector. Excessive energy consumption from inefficient buildings, in addition to the changing climate and extreme temperatures may exacerbate health impacts to occupants exposed to pollutants emitted by buildings. Therefore, applying efficient mitigating responses in buildings are necessary. In this research, external environmental and health impacts due to energy consumed in an office building in Philadelphia for winter seasons is investigated and the impact of implementing mitigating measures is assessed. EnergyPlus simulation tool will be used for modeling the U.S. Department of Energy reference office building. Hidden health costs will be measured with an impact pathway approach and will be quantified using the EcoSenseLE tool. Reducing lighting density, improving the fenestration, and modernizing the equipment are three mitigating factors which will be used. The effectiveness of the response factors will be determined for 60 years of exposure. Results of this study show improvement in fenestration to be the most cost-efficient response factor in terms of health impact.

Introduction

The gradual increase in the earth's average temperature is called global warming. The Intergovernmental Panel on Climate Change (IPCC) predicts a possible 5°C temperature increase in its extreme scenario by the end of the century (Pachauri et al., IPCC 2014) for Philadelphia which is alarming. Increased emissions produced by human activities interacts with the climate's balance and has contributed to global warming (Vong, 2016). Buildings consume high energy and are a significant participant to Greenhouse Gas (GHG) emissions (Guan et al., 2007). In addition, people living in urban regions are exposed to emissions produced by buildings. Therefore, given buildings lifespan (i.e., 60 years), it is important to understand their impact on populations health and the environment and is necessary to evaluate buildings potentials to mitigate their negative impact on their surroundings.

In 2017, approximately 40% of the total energy consumption in the U.S. was consumed by residential and commercial sectors. Results from the Energy Information Administration (EIA) 2012 Commercial Buildings Energy Consumption Survey (CBECS) show that between 1979 and 2012 the number of commercial buildings in the U.S. has increased from 3.8 million to 5.6 million. The commercial building sector is extremely diverse. However, among all the categories, offices, warehouses, and service sectors build up to approximately 50% of the commercial buildings in the U.S. with office buildings having the highest portion.

The location under study is Philadelphia which fits in the 4A climate category of the Department of Energy (DOE) having a mixed-humid climate condition. The average annual temperatures obtained from the Franklin Institute Weather Data in Philadelphia shows an increase of 1.5°C since 1874 and is expected to continue up to 5°C (IPCC A2 scenario). Buildings in the city of Philadelphia, on average, are more than 60 years old and most were built before any building regulation existed and are highly vulnerable to the changing climate. The changing climate also causes rapid occurrence of extreme events, such as urban heat island, extreme high temperatures in summertime, and extreme harsh winter seasons; therefore, assessing buildings energy performance and their associated health impacts is of high importance (Yassaghi et al., 2019).

Background

There exists a rich body of research regarding environmental and health impacts of building-related energy consumption. Blom et al. (2011) studied the environmental impact of a Dutch apartment following a comparison between utilizing electricity or gas as a primary energy used in buildings through its life cycle. Harlan & Ruddell (2011) reviewed the increased mortality and morbidity rate due to excessive heat and air pollution globally and concluded that city risk management plans with adapting and mitigating strategies to reduce GHG emissions can provide health co-benefits. Nemry et al. (2010) presents the energy consumption, environmental impacts and potential responses of 72 building types in terms of physical and geographical characteristics of the buildings through a life-cycle assessment approach. Wilkinson et al. (2007) studied the connection between energy, efficiency, and health. Younger et al. (2008) developed an approach in improving health which has been negatively impacted due to consumption through major consuming sectors in cities and highlights components that may act as adapting and mitigating factors. Overall, there should be a trade-off between indoor and outdoor health of buildings (Assefa et al., 2010). The main body of research focuses on the relationship between energy consumption of the buildings with environmental and health impacts. However, very few descriptions regarding the environmental and health impact reduction associated with mitigation responses in buildings for each climate season are available. This study aims to quantify the health co-benefits of implementing mitigating measures in buildings for the location of Philadelphia in winter seasons. The next section presents a summary of the methods used to achieve this goal.

Summary

With the use of existing typical weather files and the EnergyPlus building simulation tool, energy consumption of a sample office building for the location of Philadelphia is assessed. The impact of implementing potential mitigating factors in the building energy use is evaluated. Reducing Lighting Density (LD), improvement in fenestration (U-value), and improvement in heating Equipment Efficiency (EE) are selected as the mitigating responses. The reason for considering the aforementioned factors are due to their significant changes in building standards since 2004, which have also been determined to have high mitigating potential in buildings (Yassaghi & Hoque, 2019). With an impact pathway approach and by using the EcoSenseLE external cost of energy tool the health impacts associated with building-energy consumption are examined and presented as Disability Adjusted Life Years (DALY). DALYs is a commonly used metric used for quantifying the burden of disease from mortality and morbidity (Rasheduzzaman et al., 2019). The health impacts are also reported as monetary values and the most cost-efficient conservation measure in terms of health impact are assessed using a functional unit defined for the purpose of this paper. The outcome of implementing the three response strategies for 60 years of exposure for each response factor is presented and their effectiveness in terms of both sustainability and health are quantified.

Methodology

EnergyPlus will be used to model DOE office reference buildings constructed pre-1980 to evaluate energy consumption and GHG emissions. The case under examination has 12 floors plus basement and a total area of 46320 m^2 with a floor-to-floor height of 4m, a height of approximately 50m with a Window to Wall Ratio (WWR) of 0.35 having windows on all four sides of the building (Table 1).

Parameter	Unit	Pre-1980	Res.
Wall	m^2K/W	1	
Roof	Type	IEAD[1]	
	m^2K/W	2	
Foundation	Type	4-inch Slab	
	m^2K/W	0.54	
Window	W/m^2K	5.8	3.2
	SHGC	0.54	
Infiltration	$m^3/h/m$	0.223	
LD	W/m^2	2.69 (Ext)	
	W/m^2	16.8 (Int)	10.2(Int)
PLD[3]	W/m^2	10.8	
Occupancy	m^2/person	18.58	
Ventilation	L/s person	9.44	
System		MZ-VAV[4]	
Heating	Type	Boiler	
	%	70	80
Cooling	Type	Chiller	
	COP	5.1	

[1] Insulation Entirely Above Deck
[2] Solar Heat Gain Coefficient
[3] Plug Load Density
[4] Multizone Variable Air Volume

Table 1: Building's physical characteristic.

As mitigating responses, an LD of 10.2 W/m^2, boiler efficiency of 80% and window U-value of 3.2 W/m^2K is implemented, which are in accordance to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards 90.1 2004. This study focuses on health impacts of building energy consumption in winter seasons. The costs associated to fully replacing the conservation measures is calculated excluding the maintenance and installment costs. And results are compared to their co-benefits of reducing health impacts.

Health impacts are measured as DALY values. The World Health Organization (WHO) Defines DALY as: "One DALY can be thought of as one lost year of "healthy" life. The sum of these DALYs across the population, or the burden of disease, can be thought of as a measurement of the gap between current health status and an ideal health situation where the entire population lives to an advanced age, free of disease and disability." DALY values due to exposure to classical pollutants such as NMVOC, NOx, PM10, SO_2 and CO (Harlan & Ruddell, 2011) are examined. Environmental and health impacts caused by air pollution are assessed using an impact path approach. The impact pathway approach (Figure 1) is a bottom-up approach to assess environmental and health impacts due to pollution and presents output in the form of DALY and Global Warming Potential (GWP).

The output of the EnergyPlus tool is used as input data to calculate the environmental and health impacts using the EcoSenseLE tool.

The three mitigating factors are implemented and results of the energy consumption as well as environmental impacts associated to the responses are presented. To compare the cost-efficiency of the conservation measures, a functional unit is defined (Cost Beneficial Functional Unit) which is the cost of DALY reduction compared to base case over the cost of implementing response measures.

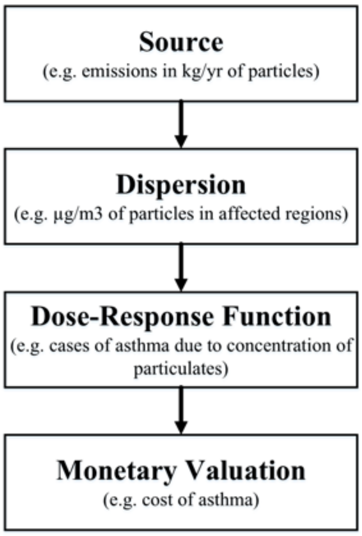

Figure 1: The steps to an impact pathway analysis of air pollution (Bickel & Friedrich, 2005).

	LD (Fluorescent)	Double pan window	Hot water boiler
Life period	25,000 (hrs)	30 (years)	6 (years)
Cost	2 $/20Watt	50 $/window	800 $/million BTUH
Building requirement	10.2 Watt/m²	4200 m²	15 million BTUH
Factors	**Calculations**		**Costs**
Windows	12,240 m² (area) × 0.35 (WWR) × 50$/window area × 2 (# times replaced)		$428,400
Boiler	800 $/million BTUH × 15 million BTUH × 10 (# times replaced)		$120,000
Light bulbs	2$/20 Watts × 10.2 Watt/m² × 46320 m² (area) × 6 (# times replaced)		$283,478

Table 2: Cost of implementing the conservation measures.

Equation 1:

$$\mathrm{CBFU}=\frac{Cost\ of\ DALY\ reduction}{Cost\ of\ \ mitigating\ factor}\times 100$$

The lower the CBFU, the cost beneficial the conservation is. This is measured in terms of monetary values which reflect cost of health impacts. An efficient CBFU is either the cost of implementing the mitigating measures is very low or the reduction in cost of DALY is very high due to implementing the mitigating factor, which in either case is defined to be cost beneficial.

The cost of implementing the conservation measures along with their life period and standard requirement of the building is presented in Table 2. The boiler size needed to fulfill the building's demand for the case of implementing a more efficient heating application is 15 million BTU/hr (4400000 Watts) hot water boiler with an 80% efficiency. The lighting density of the building is 10.2 W/m². The costs associated to fully replacing the conservation measures is calculated excluding the maintenance and installment costs. And results are compared to their co-benefits of reducing health impacts.

It was assumed that exposure occurs in all hours of the day and for a 60-year period in winter seasons. The source of emission of the building is approximately 50 meters above ground level but it was assumed this occurs in 100 meters above ground level due to limitations of the EcoSenseLE tool. Although the building-energy assessment was done for Philadelphia, but due to the limitation of the EcoSenseLE tool, the health impacts analysis was conducted assuming a single emission point located in Berlin. The reason for selection of Berlin was its similarity to Philadelphia's climate condition. EnergyPlus™ reports annual results, but here it was assumed for a period of 60 years, the weather, exposure, building, and consumption pattern remains unchanged from year to year.

Results

Table 3 shows the results of the heating and cooling consumption of the office building for a 60-year period of time. In addition, the classical pollutants emitted from the building and the health impact in terms of DALY and their health cost is shown.

	Unit	TMY3			
		Base	**EE**	**LD**	**U Value**
Heating	TWh	0.129	0.122	0.138	0.088
NMVOC	Tons	1.25	1.19	1.34	0.87
NOx	Tons	22.64	21.54	24.19	15.68
PM10	Tons	1.72	1.64	1.84	1.19
SO2	Tons	0.13	0.12	0.14	0.09
CO	Tons	19.10	18.17	20.40	13.23
DALY	Yrs	2.84	2.70	3.04	1.97
Cost	$	254373	241973	271807	176175

Table 3: Summary of the energy consumption, emissions, and health impacts.

The results for heating consumption showed a 5% decrease, 7% increase, and 31% decrease when improving EE, LD, and fenestration improvement, respectively. Improvement in fenestration showed a significant reduction in heating and from an energy point of view can be ranked as the most effective response compared to the other two. It was also found that in wintertime, improvement in EE and fenestration reduces the DALY values by 5% and 30%, respectively, and reduction in LD resulted in a 7% increase in DALY. The health impact results match with the findings of energy consumption, which is also expected. When energy consumption reduces, emissions from the building decreases and the environmental and health impact become lower. However, the question is to quantify these response factors in units of money and assess their effectiveness.

From Table 2 the total cost of installing new double-pane windows in the entire facility through a 60-year period is $428,400, replacing a boiler with the needed capacity and an 80% efficiency is $120,000, and to completely replace the interior light bulbs with fluorescent lights with a power of 20W is $283,478. Changing the boiler as a mitigating factor is the cheapest approach. However, the results should be compared to the health benefits they provide to come up with the most cost-efficient measure.

Factor	DALY Cost Difference to Base ($)	Cost of implementation ($)	CBFU (%)
Windows	-78,199	428,400	-18.25
Boiler	-12,400	120,000	-10.33
Light bulbs	17,433	283,478	6.15

Table 4: Summary of the cost analysis.

As shown in Table 4, although the cost of improving fenestration is the highest compared to other mitigating factors, the reduction of health impacts compared to the base case outweighs the higher cost compared to boiler efficiency improvements. Reducing LD, however, exacerbated the results, because it increases heating requirements. However, it is expected to play a significant role in reducing energy consumption in summer seasons, which requires deeper examination and does not fit in the scope of this study.

Conclusion

Pollutants due to burning of fossil fuels can cause many diseases and could be fatal. The interconnection between climate change and air pollution requires more attention. Our findings suggest that fenestration improvements had the highest cost of implementation but yielded the best CBFU and resulted in a greater health impact reduction compared to other mitigating factors. This means when developing response strategies, trade-offs should be made. Not all mitigating factors build a synergic response, and therefore, understanding their performance in terms of energy and health is necessary.

Discussion

Mitigation measures in buildings can be conflicting and policies to address a trade-off should be made to develop a sustainable and health-beneficial built environment. It was found that improvement in fenestration can have a significant reduction in heating energy consumption and health impacts associated with it. However, the costs of replacing efficient windows is high and allocating governmental subsidies to encourage private sectors to abide by resilience and sustainable measures can have both short-term benefits for buildings in terms of energy consumption and long-term regional co-benefits in terms of health and sustainability.

It was found that buildings emissions can cause health risks to occupants in direct exposure to them. Utility bills only reflect energy consumption and price of consuming energy. However, given the current trends of climate change, it is necessary that strict policies be developed to reduce buildings carbon footprint to enhance a more sustainable and healthier environment. One way to encourage private sectors to reduce their carbon emissions is to reflect their carbon footprint and their associated health impacts on utility bills and set acceptable boundaries of emissions. For buildings exceeding the boundaries, strict fines should be applied to compensate the health impacts caused by them.

Acronyms

ASHRAE	American Society of Heating Refrigeration and Air-conditioning Engineers
CBECS	Commercial Buildings Energy Consumption Survey
DALY	Disability Adjusted Life Year
DOE	Department of Energy
EE	Equipment Efficiency
EIA	Energy Information Administrative
GHG	Greenhouse Gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
LD	Lighting Density
NMVOC	Non-Methane Volatile Organic Compound
PM	Particulate Matter
WHO	World Health Organization
WWR	Window to Wall Ratio

References

Assefa, G., Glaumann, M., Malmqvist, T., & Eriksson, O. (2010). Quality versus impact: Comparing the environmental efficiency of building properties using the EcoEffect tool. *Building and Environment, 45*(5), 1095–1103.

Bickel, P., & Friedrich, R. (2005). Externalities of Energy. Methodology 2005 Update. European Commission EUR, 21951.

Blom, I., Itard, L., & Meijer, A. (2011). Environmental impact of building-related and user-related energy consumption in dwellings. *Building and Environment, 46*(8), 1657–1669.

EIA, U.S. Department of Energy, Energy Information Administration. Retrieved from (Accessed April 2019): https://www.eia.gov/consumption/commercial/reports/2012/buildstock/

Guan, L., Yang, J., & Bell, J. M. (2007). Cross-correlations between weather variables in Australia. *Building and Environment, 42*(3), 1054–1070.

Harlan, S. L., & Ruddell, D. M. (2011). Climate change and health in cities: impacts of heat and air pollution and potential co-benefits from mitigation and adaptation. *Current Opinion in Environmental Sustainability, 3*(3), 126–134.

Nemry, F., Uihlein, A., Colodel, C.M., Wetzel, C., Braune, A., Wittstock, B., Hasan, I., Kreißig, J., Gallon, N., Niemeier, S., & Frech, Y. (2010). Options to reduce the environmental impacts of residential buildings in the European Union—Potential and costs. *Energy and Buildings, 42*(7), 976–984.

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., Church, J.A., Clarke, L., Dahe, Q., Dasgupta, P., & Dubash, N. K. (2014). Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p. 151).

Rasheduzzaman, M., Singh, R., Haas, C. N., Tolofari, D., Yassaghi, H., Hamilton, K. A., Yang, Z., & Gurian, P. L. (2019). Reverse QMRA as a Decision Support Tool: Setting Acceptable Concentration Limits for Pseudomonas aeruginosa and Naegleria fowleri. *Water, 11*(9), 1850.

Vong, N. K. (2016). *Climate Change and Building Energy Use: Evaluating the Impact of Future Weather on Building Energy Performance in Tropical Regions* (Doctoral Dissertation). University of Hawai'i at Manoa. ProQuest ID: 10295977, 2016. http://hdl.handle.net/10125/45569

Wilkinson, P., Smith, K. R., Beevers, S., Tonne, C., & Oreszczyn, T. (2007). Energy, energy efficiency, and the built environment. *The Lancet, 370*(9593), 1175–1187.

Yassaghi, H., & Hoque, S. (2019). An Overview of Climate Change and Building Energy: Performance, Responses and Uncertainties. *Buildings, 9*(7), 166.

Yassaghi, H., Mostafavi, N., & Hoque, S. (2019). Evaluation of current and future hourly weather data intended for building designs: A Philadelphia case study. *Energy and Buildings, 199,* 491–511.

Younger, M., Morrow-Almeida, H. R., Vindigni, S. M., & Dannenberg, A. L. (2008). The built environment, climate change, and health: opportunities for co-benefits. *American Journal of Preventive Medicine, 35*(5), 517–526.