INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 2, Issue 3, 2011 pp.415-426
Journal homepage: www.IJEE.IEEFoundation.org

CO_2e emissions from HVAC equipment and lifetime operation for common U.S. building types

Aik Jong Tan, Darin W. Nutter

Department of Mechanical Engineering, University of Arkansas, Fayetteville, AR 72701, USA.

Abstract
Greenhouse gas emissions associated with the lifetime operational energy use and equipment manufacture of the heating, ventilating, and air-conditioning equipment for ten common commercial building types were presented. The influence of operating the building in several different climate regions were included in the analysis. Emission factors for natural gas and each of the three North American Electric Reliability Corporation major interconnections were used. Results found emissions associated with a building's lifetime operational energy use were dominant compared to those from the equipment manufacture and production which ranged from 1.9 – 4.2%. Primary factors that influenced the emission rates were found to be regional electrical emission factors, building type, and climate.

Keywords: Greenhouse gas emissions, Commercial buildings, HVAC equipment, Operational energy.

1. Introduction and background

Buildings contribute to greenhouse gas (GHG) emissions through not only the fossil fuel-based electricity and fuel used to operate them, but also the emissions associated with the manufacture and upstream raw material production of building construction materials. Several studies have been conducted on the manufacturing and production (M&P) energy required to construct residential buildings and to a lesser extent, commercial buildings [1-7]. These works primarily focused on the manufacturing and production energy and emissions from the infrastructure material (i.e., building envelop) such as concrete, steel, and wood; and, energy consumed during the construction of buildings. However, very few studies have been conducted that focus on the impact from a building's heating and cooling equipment.

Although the 'embedded' energies in the heating, ventilating, and air-conditioning (HVAC) equipment from material and manufacture can be large in magnitude, it is generally considered small, when compared to the lifetime of operational energy consumed [8-10]. Simonson's study [11] on residential ventilation units in cold climate found the lifetime operational energies was as much as 200 times more than the energy needed to produce the ventilation units. Furthermore, the greenhouse emissions from the upstream M&P of the ventilation unit were only 8% of the operational emissions. In Nyman's study [12] on air-handling units (AHUs) in office buildings, it was discovered that the largest environmental impact came from the operation of the AHUs. Nyman also discovered that using a smaller AHU had a 40% higher potential harmful effect on the environment compared to using a normal sized AHU over the lifespan of the AHU. Although the smaller AHU had about 20% lower emissions during its production due to less material required, it was also less efficient than a normal AHU and consumed more energy over its lifetime. In Rey's study [13] on the comparison of heat pumps and boilers in a commercial building, it was discovered that a heat pump was a better choice than boilers, from the view of life cycle assessment and life cycle cost. Rey showed the environmental impact caused by the manufacturing of heat pumps was larger than manufacturing impact of a boiler. Yet the emissions from the operation of a natural gas boiler had a more significant impact than a high efficiency electric heat pump. Shah et al. [14] performed a life cycle assessment of residential heating and cooling systems in four US regions. They showed that the HVAC equipment has different environmental impact based on the regional climate and energy source. In particular, it was shown that operating electric heat pumps in Oregon had the lowest emissions when compared to operating a furnace and air-conditioner combination to a boiler and air-conditioner system. This was primarily due to the electricity fuel mix in Oregon, as it was mostly hydro-electric power. Shah also concluded that heat pumps had the highest impacts when the major proportion of the electricity consumed was from fossil fuel sources. Another study [15], written in Japanese, apparently compared lifetime operational energies to the HVAC equipment's M&P energies for residential buildings in Japan. Through the interpretation of English-written titles and graphs, it was found that operational energies and related emissions were significantly higher. Sato showed that the HVAC's operational energy was 98%, while the manufacturing and production energy was only 2%.

Deru [16] has recently published work on building-related emissions. He has highlighted the relative significance of commercial buildings and many of the issues related to GHG computations, such as the proper determination (and use) of upstream emission factors and the many complexities of electricity-based emissions. As an effort to further understand the broad implications of commercial buildings and their potential GHG emissions, this paper discusses the GHG emissions, both lifetime operational and M&P, from commercial buildings' HVAC equipment in different geographical locations and climate regions; and, for various building types and fuel sources.

2. Methodology and approach

Four primary sources of data were used in this study: the *DOE Commercial Building Benchmark Model* [17], *2002 RSMeans Mechanical Cost Data* [18], DOE *Net Zero Energy Commercial Building Initiative Models* [19], and Economic Input-Output Life Cycle Assessment Model (EIO-LCA) [20]. Information and data regarding building specifications and operational energy consumption were obtained from the *DOE Commercial Building Benchmark Model* and DOE *Net Zero Energy Commercial Building Initiative Models* [19]. The GHG emissions related to buildings' HVAC equipment were obtained from the EIO-LCA tool by inputting the HVAC equipment manufacturer's cost estimation obtained from the 2002 *RSMeans Mechanical Cost Data* [18]. The authors chose to use the EIO-LCA method developed by the Green Design Institute of Carnegie Mellon University. This method allows the estimation of GHG emissions based on the economic input and output in a particular sector of industry. It uses information on the economical transaction of materials and manufactured goods to estimate the total emissions of a particular sector due to those activities. Using an estimated monetary amount spent on HVAC equipment, the total emissions from the production of HVAC equipment was determined. The 2002 US National Producer Price Model from the US 2002 benchmark in the EIO-LCA [20] database was applied in this study. HVAC equipment costs from the *2002 RSMeans Mechanical Data* [18] were based on a cost per unit area basis. Varying costs associated with building type, city location, national average HVAC equipment cost, and individual city's labor and material cost were incorporated. Since this approach is based on cost, one limitation is that variations due to equipment capacity were not directly captured.

The GHG emissions from the operation of a building's HVAC equipment are influenced by numerous factors; and those included in this study were local climate, building type, building size, HVAC equipment capacity, geographical location, and on-site emissions. Each is discussed further below.

The climate influences a building's emissions due to the required HVAC equipment size, load, and runtime. ASHRAE 90.1 Standard [21] has subdivided the United States into 8 different climate zones. Within these climate zones, there are moist, dry and marine regions, as indicated in Figure 1. The need for indoor climate control is thus different. The indoor climate control for a building in Florida would be primarily cooling whereas a building in the Minnesota would be heating. In this study, 15 cities were selected. The cities were located in the different climate zones and regions across the United States. The climate in these cities represents the regional climate of that particular zone. Furthermore, the selected cities correspond to those selected in the *DOE Commercial Building Benchmark Model* [17]. Except where otherwise indicated in Table 1, the weather data for these cities were used for this study.

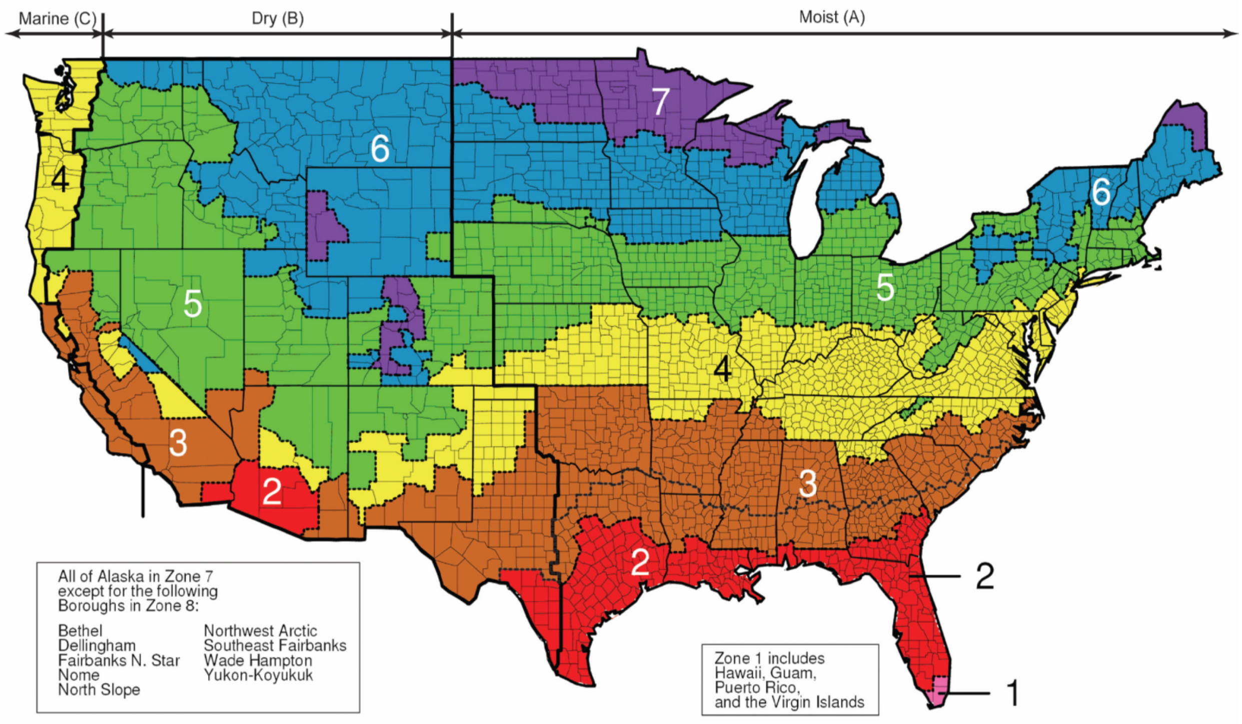


Figure 1. The climatic zone in the United States [21]

Table 1. Cities, climate zones, and representative weather locations used in this study [17]

Number	Climate Zone	Representative City	TMY2 Weather Location
1	1A	Miami, FL	Miami, FL
2	2A	Houston, TX	Houston, TX
3	2B	Phoenix, AZ	Phoenix, AZ
4	3A	Atlanta, GA	Atlanta, GA
5	3B1	Los Angeles, CA	Los Angeles, CA
6	3B2	Las Vegas ,NV	Las Vegas, NV
7	3C	San Francisco, CA	San Francisco, CA
8	4A	Baltimore, MD	Baltimore, MD
9	4B	Albuquerque, NM	Albuquerque, NM
10	4C	Seattle, WA	Seattle, WA
11	5A	Chicago. IL	Chicago-O'Hare, IL
12	5B	Denver, CO	Boulder, CO
13	6A	Minneapolis, MN	Minneapolis, MN
14	6B	Helena, MN	Helena, MN
15	7	Duluth, MN	Duluth, MN

The United States has three main grids in the generation and distribution of electricity. These grids are the Eastern Interconnection, Western Interconnection, and Electric Reliability Council of Texas (ERCOT). The Eastern Interconnection encompasses the vast area from the area east of the Rocky Mountains to the Atlantic coast of the United States, including some parts of Texas. The Western Interconnection covers most area west of the Rocky Mountains to the Pacific Ocean. Electric Reliability Council of Texas (ERCOT) covers mainly the state of Texas. Although the North American Electrical Reliability Corporation (NERC) oversee these grids through a 10 regional reliability councils, its three main grids are virtually independent and have very few connections, and energy transfer among them (Figure 2). The emission factors presented in Torcellini and Deru's [23] "*The Source Energy and Emission Factors for Energy Use in Buildings*" were used in this study to account for the source emissions.

The rate of GHG emissions is different within these three large Interconnection regions, due to the different factors of emission within the region. Over 70 percent of the electricity generated in the United States is from fossil fuels – coal, fuel oils, and natural gas. The extraction, transportation, processing, and purification of these fuels consume energy and produce GHG. The method used in electric power generation also contributes to the different rate of GHG emissions. Thus, the emission factors from the different interconnect regions are different. For example, the energy source for most of electricity generated in Texas (ERCOT) is from fossil fuel sources [14], thus the combined pre-combustion and combustion emission factor was found to be larger than other regions. Most electrical power plants are located a distance away from the consumer; therefore, losses occur during transmission and distribution (T&D) of electrical power. These losses were also taken into account to obtain a more accurate understanding of the total GHG emissions. Table 2 contains the eGRID pre-combustion and combustion emissions factors, and the percentage of losses during transmission and distribution for each interconnect region. Table 3 shows the on-site fuel energy emissions for fuels used in building heating systems.

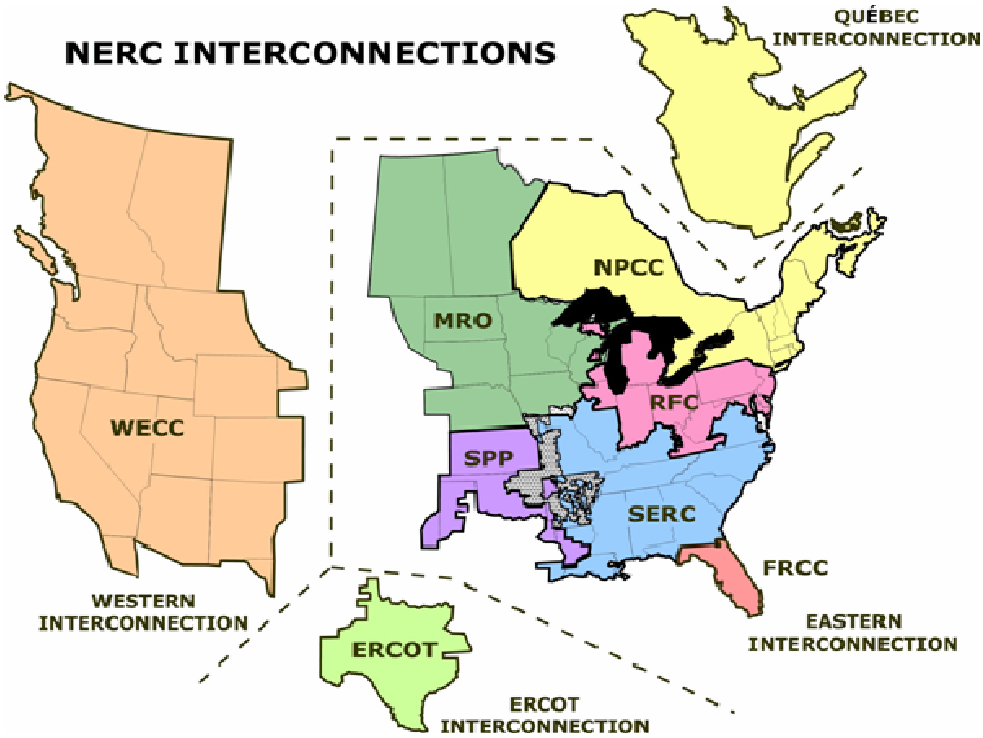


Figure 2. NERC interconnection of North America [22]

Table 2. eGRID emission factors [23]

eGRID Region	a. Combined pre-combustion and combustion emission factor ($kgCO_2e/kWh$)	b. Transmission and Distribution (T&D) Losses (%)	a + b Total regional CO2e emission rate ($kgCO_2e/kWh$)
Eastern	0.788	9.6	0.8696
Western	0.594	8.4	0.6439
ERCOT	0.834	16.1	0.9683
National	0.758	9.9	0.833

Table 3. On-site fuel energy emission factors [23]

On-site Fuel (units)	a. Pre-combustion and combustion emission factors (kg CO_2e/unit)	b. Combustion emission rate (kg CO2e/unit)	a + b Combined pre-combustion and combustion emission factors (kg CO_2e/unit)
Diesel (gallon)	2.08	10.34	12.42
Natural Gas (MMBtu)	12.24	54.18	66.42
Natural Gas (CCF)	1.26	5.58	6.84

The size of a building influences total greenhouse gas (GHG) emissions, but floor area of a building is not the only factor involved. The function and purpose of a building also contribute to the amount of GHG emissions. The operation of the HVAC equipment of a supermarket would, for example, produce more GHG emissions than a warehouse.

Since buildings are different in size, location, architectural design, functionality, and construction material use, it is difficult to conduct studies, research and comparisons without some common building specification. Until recently, no standard building models have been available to simulate building energy use; however, the *DOE Commercial Building Benchmark Models* [17] now provides such building models. The benchmark building models represent the energy use from approximately 70% of the commercial buildings in the US. In total, fifteen benchmark buildings, across 16 US climate zones, were developed. Each benchmark model included the description of building floor area, building envelope, and HVAC equipment type based on building vintage (pre-1980, post-1980 and new construction). This study focused only on new building construction, its energy consumption and corresponding GHG emissions.

Since the focus of this study is on the HVAC equipment, projections of the operational energy required for the building's HVAC equipment, over its lifetime, is necessary. Monthly electricity and natural gas consumption for 10 of the 15 building types (see Table 4) and 15 of the 16 climatic locations were chosen, Alaska's climate zone #8 was excluded. Five of the available 15 building types from *DOE Commercial Building Benchmark Model* [17] were omitted from this study due to data unavailability; these buildings were large office, strip mall, fast food restaurant, outpatient health care and large hotel. Each building's HVAC equipment used a combination of natural gas and electricity for its operation. The specific systems, listed in Table 4, included package air conditioning, individual room air conditioner, chiller, individual space heater, boiler and furnace.

Data from the 2002 RSMeans Mechanical Cost Data [18] was used to provide the consumer cost of the HVAC equipment for each typical building. The median area cost of HVAC ($\$/ft^2$) for the building types listed above were used in the computation. This cost included the contractor's overhead and profit, but not the cost of site work, architectural fees and land cost. In addition, the median area cost was the national average value, adjusted for city-specific cost of labor and materials. A larger building of the same specification, built in the same locality, would typically have a lower per square foot cost. So, to determine the final consumer cost for the HVAC equipment, a 'size modifier' adjustment was made to account for this difference.

In order to estimate the HVAC equipment's manufacturing and production (M&P) GHG emissions, the HVAC manufacturer's cost was needed. The manufacturer's cost or mark-ups [24] included all parties in the distribution channel; HVAC equipment manufacturer, wholesaler, small mechanical contractors, general contractors and the customer. Figure 3 shows the parties involved in the distribution channel. The national average and individual states' price markups data were also incorporated from the source. When an individual state's price markup was not available, the national average was used. Furthermore, an average 7% sales tax was applied.

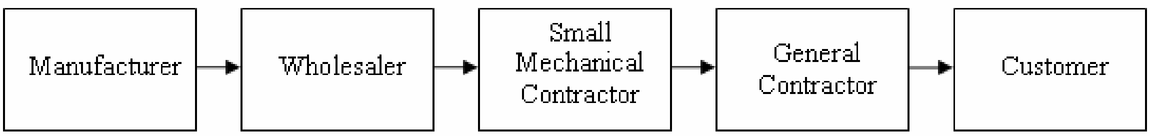


Figure 3. Flowchart of the standard price markup for HVAC equipment

Table 4. DOE Commercial Building Benchmark, Equivalent RSMeans Building Types and Typical Size Abbreviated system types below are package air conditioning units (PACU), individual room air conditioners (IRAC), and individual space heater (ISH) [17]

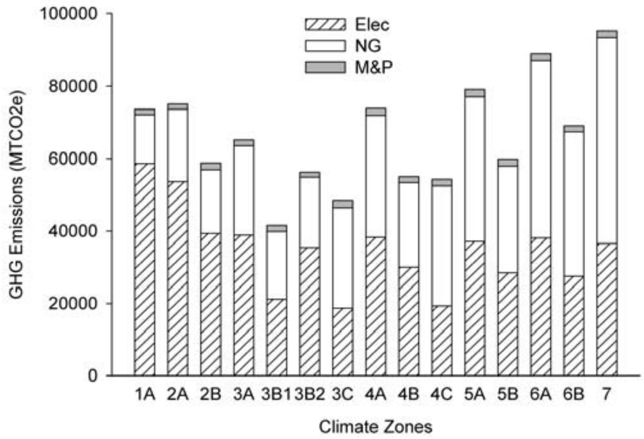
Benchmark Model Building Types [Torcellini et al.]	RSMeans Equivalent Building Type [RSMeans]	Floor Area, ft^2	Typical Size Gross, ft^2	Natural Gas Heating System	Electric Cooling System
Medium Office	Office Mid Rise	53,628	120,000	Furnace	PACU
Small Office	Office Low Rise	5,502	20,000	Furnace	PACU
Warehouse	Warehouse & Office Combination	52,045	25,000	Furnace	PACU
Stand-Alone Retail	Retail Stores	24,692	7,200	Furnace	PACU
Primary School	Schools Elementary	73,959	41,000	Boiler	PACU
Secondary School	Schools Senior High	210,887	101,000	Furnace	Chiller
Supermarket	Supermarkets	45,004	44,000	Furnace	PACU
Restaurant	Restaurants	5,502	4,400	Furnace	PACU
Hospital	Hospitals	241,351	55,000	Boiler	Chiller
Motel	Motel	42,554	40,000	ISH	IRAC

For example, an amount of $332,750 was spent to purchase HVAC equipment to equip a medium size office building in Houston. Starting with manufacturer’s cost as 1, the mark ups were as follows, General Contractor, 1.24; Mechanical Contractor, 1.43; Wholesaler, 1.39; and average sales tax, 1.07. Therefore, the manufacturer’s cost was found to be $126,172. With the manufacturer’s cost of HVAC equipment determined, the HVAC M&P GHG emissions were computed with the EIO-LCA model [20]. The “US 2002 Producer Price Model” was used along with the “Machinery and Engines” and “Air conditioning, Refrigeration, and Warm Air Heating Equipment” for the appropriate industry and sector categories.

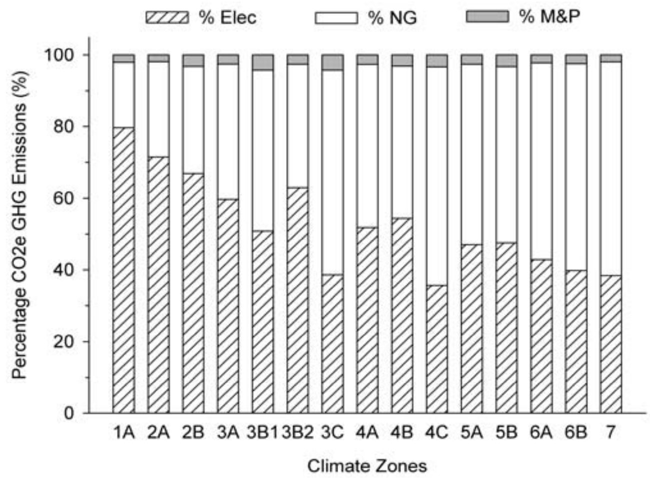
3. Results and discussion

The following section presents selected results from the study and provides discussion and analysis with regard to overall GHG emissions for the various building types, climate regions, electrical interconnect regions, and GHG contributor (i.e., electricity, natural gas, and HVAC manufacturing and production (M&P)). In addition, selected building or climate zone cases are presented for discussion.

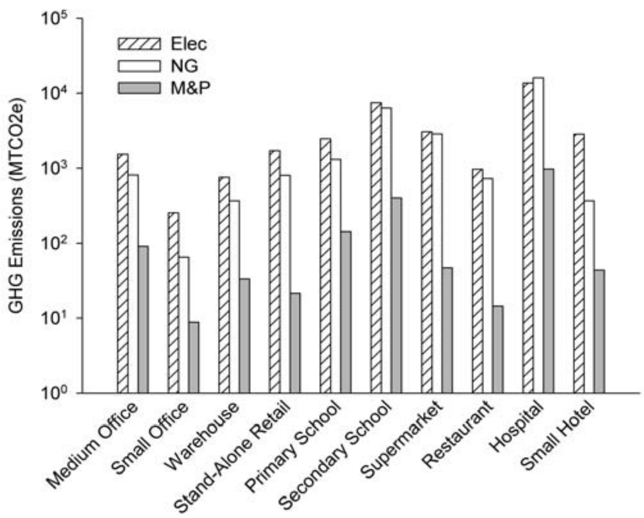
Figures 4(a) through 4(c) show GHG emissions for all buildings across each climate region. Figure 4a shows the individual emissions from each of the 10 building types, summed for each climate region. Figure 4b presents the information in percentage format. Similarly, Figure 4c gives the average emissions for each building type across all climate zones. It was evident that the GHG emissions generated from the operation of HVAC were significantly larger than GHG emissions as compared to the HVAC M&P. Although the source emissions and local climates vary, only 2.8% (on average) of GHG emissions for the twenty year lifespan operation of HVAC equipment can be attributed to HVAC M&P. Los Angeles (3B1) had the largest HVAC M&P portion at 4.2%, while the minimum was in Houston (2A) at 1.9%. These percentages primarily change due to the climate based HVAC equipment’s operational energies and the difference in electricity emission factors. In other words, San Francisco’s electricity and natural gas usage is much smaller than Miami’s; and, the Western Interconnect emission factor is 25.9% smaller than the Eastern interconnect. More importantly, the largest portion of the GHG emissions was from the ‘operational’ consumption of electricity during the operation of HVAC equipment, 54% on average. Similarly, natural gas consumption accounted for 46%.



(a)



(b)



(c)

Figure 4. (a) Total CO2e GHG emissions for all buildings within each climate zone, (b) percentage total CO2e GHG emissions for all buildings within each climate zone, and (c) average CO2e GHG emissions and sources for each building type across all climate zones

Figures 5(a) and 5(b) provide a comparison of electricity and NG energy consumption percentages and the corresponding GHG emissions percentages. It was evident that the use of electricity in the operation of HVAC equipment generates the majority of GHG emissions. For example, the portions of electricity

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online)

and NG used in San Francisco (3C) were 19.2% and 80.8%; however, the GHG emissions were 40.3% electricity and 59.7% NG. Since electricity use, and therefore GHG emissions, is driven primarily by air conditioning, GHG emissions decrease from warmer to colder climate zone (i.e. from climate zone 1 to climate zone 7). Inversely, the GHG emissions from natural gas increase from warmer climate to colder climate regions. The amount of GHG emissions from natural gas varied from 13,461 $MTCO_2e$ in Miami (1A) to 56,784 $MTCO_2e$ in Duluth (7).

Although Phoenix (2B), Los Angeles (3B1), and Helena, MT (6B) are located in the same NERC interconnection region, the Western Interconnects, their GHG emissions from HVAC operation were very different. This indicated that local climate had a significant impact on GHG emissions. Even though modeled building types were the same in this comparison, the HVAC equipments heating and cooling loads were significantly different.

Emissions from electricity consumption are significantly higher than direct-fired fuel such as natural gas. For example, the smallest emission rate in the NREC Region was in the Western Interconnect, 0.6439 kgCO2e per kWh of electrical energy, which was equivalent to 188.72 kgCO2e per MMBtu site energy. The emission factor from the consumption of natural gas was only 66.42 kgCO2e per MMBtu. This disparity is exacerbated since much of the electricity generated in the United States is from the combustion of coal. It can be seen from Figure 6, that ERCOT and Eastern interconnects had larger GHG emissions when compared to the Western. Aside from the influence of input fuel, ERCOT also has a very high transmission and distribution (T&D) losses (see Table 2).

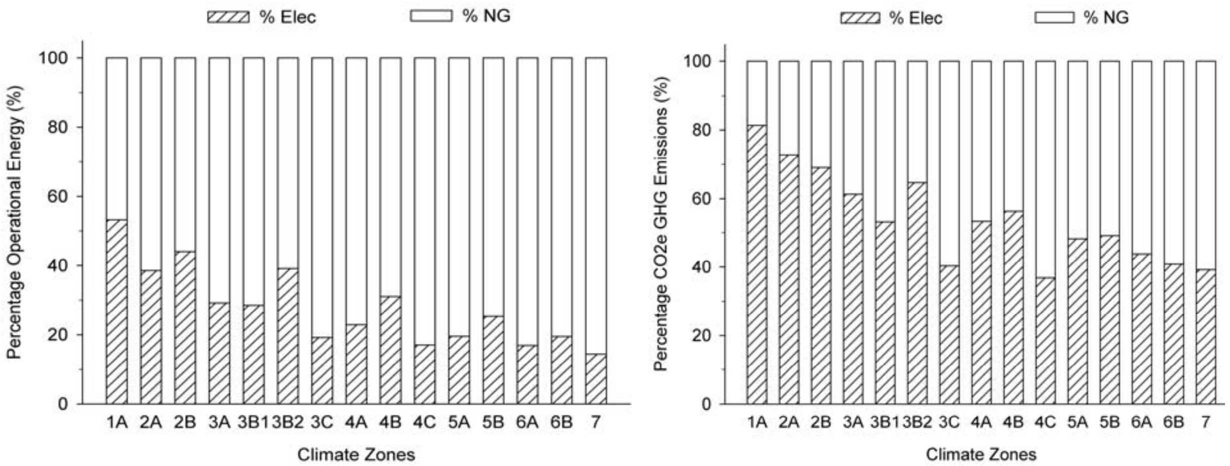


Figure 5. (a) Percentage total operational site energy for all buildings within each climate zone, and (b) percentage CO2e emissions of operational energy for buildings within each climate zone

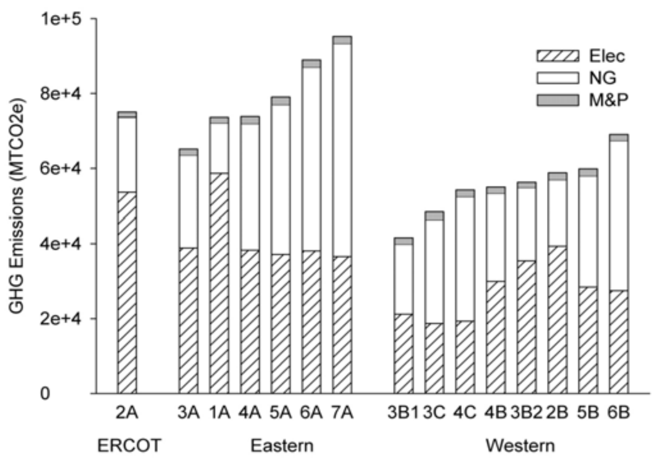
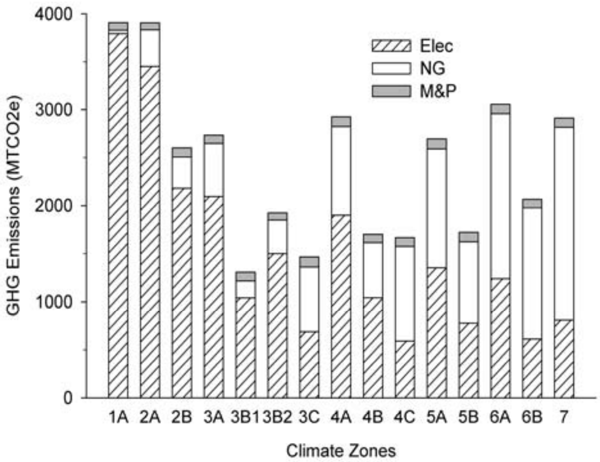


Figure 6. GHG emissions comparison of ERCOT, Eastern and Western Interconnects

As expected, emissions vary as a function of building type. As an example, Figures 7 and 8 provide a comparison between office and hospital buildings. Hospitals were found to be large emitters due mainly to total floor area, related internal heat gains, and the use of a NG boiler. In comparison, the hospital gross floor area was 241,351 ft^2 and 53,628 ft^2 for the medium office building. The hospital's internal heat gains were significantly larger than other building types, due primarily to people (1291) and related ventilation and, to a lesser amount, the load from internal equipment and lights. For example, the hospital average lighting and plug loads were 12.68 W/m^2 and 23.18 W/m^2, respectively; likewise, lighting and plug loads were 10.76 W/m^2 and 8.07 w/m^2, respectively for the medium office building.

Building location or climate zone can have an influence on emissions. A closer look at Figures 7 and 8 (a and b) show that both the hospital and office buildings' GHG emissions vary according to climate zone, but not to the same extent. For example; the minimum GHG emissions generated from the electricity use in medium office building was in Seattle (4C), 589 $MTCO_2e$. The maximum was in Miami (1A), 3,793 $MTCO_2e$, 6.4 times that of Seattle. As a contrast to medium office buildings, the variation of GHG emissions for hospital buildings in different climate zones from the use of electricity was smaller. Maximum GHG emissions from the use of electricity was 19,991 $MTCO_2e$ in Duluth, MN (7) and the minimum was 8,437 $MTCO_2e$ in Los Angeles, CA (3B1), a maximum to minimum ratio of 2.4.



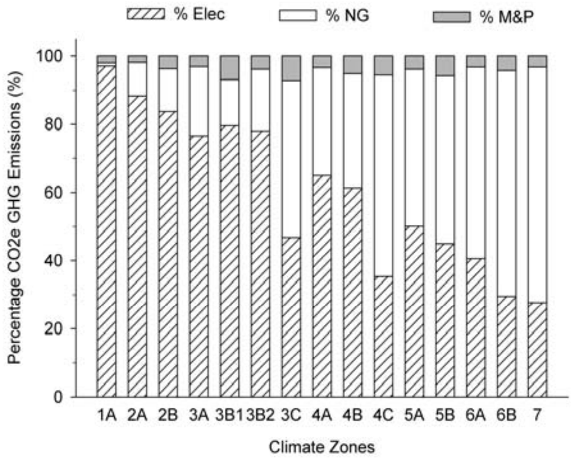


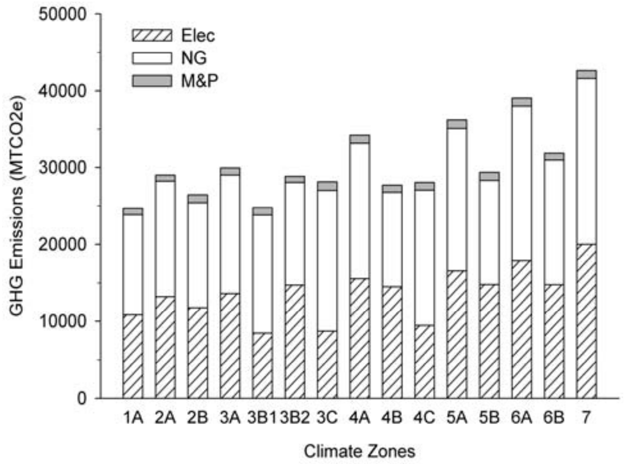
Figure 7. (a) CO2e GHG emissions of medium office for all climate zones, and (b) percentage CO2e GHG emissions of medium office for all climate zones

Furthermore, it appeared that a hospital building in colder climates had somewhat higher GHG emissions from electricity consumption than an identical hospital building in warmer climates. For example, the GHG emissions from electricity consumption in hospitals in Minneapolis (6A) and Duluth (7) during the winter months of December and January were in fact larger than the summer months. For Minneapolis (6A), GHG emissions from electricity consumption in hospitals during December and January were 116 MTCO2e and 122 MTCO2e, during July and August were both 45 MTCO2e. For Duluth (7), during December and January were 122 MTCO2e and 129 MTCO2e, during July and August were both 45 MTCO2e.

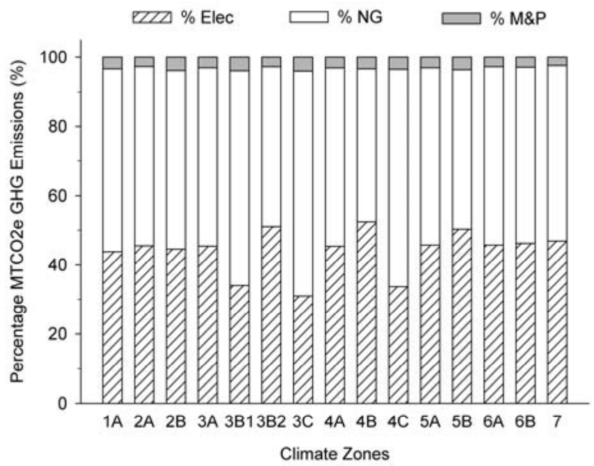
After careful inspection of *DOE Commercial Building Benchmark Models* data for hospital buildings, it was found that hospital buildings were modeled with electrical-steam humidification system that utilized electricity. Buildings located in colder climate region would require more humidification, which increased the electricity consumption; hence the high GHG emissions for hospital in colder climate region. Since the colder climate in Chicago is also a drier climate, more humidification is required. Finally, the GHG emissions of NG were as expected, increasing for cooler climates. The ratio of maximum to minimum was found to be 1.8, which was smaller compared to electricity's GHG emission from medium office buildings, which was found to be 52.8. The hospital's smaller ratio was mostly due to the year-round operating schedule, high internal heat gains, and NG having a constant emission factor.

Identical buildings in different geographic location have different GHG emissions. Comparing buildings in Miami (1A), Seattle (4C), and Chicago (5A) (see Figures 9-11), hospital buildings had the largest GHG emissions among all the building types. Generally, the second highest emitter, secondary schools varied significantly. A large portion of GHG emissions for secondary schools in Miami (1A) was from the use of electricity for cooling; but for Seattle (4C) and Chicago (5A), the majority of emissions were from the use of NG heating. The emissions trend between secondary school and all other buildings of Chicago (5A) and Seattle (4C) appeared similar.

Figure 9 shows that within the same climate region of Miami (1A), secondary school and hospital buildings have some of the largest GHG emissions. Although the hospital building (241,351 ft^2) has a slightly larger floor area than a secondary school (210,887 ft^2), the GHG emission for a hospital building was 52**%** larger. Hospital buildings in Miami (1A), Seattle (4C) and Chicago (5C) had GHG emissions of 24,688 $MTCO_2e$, 28,040 $MTCO_2e$, and 36,193 $MTCO_2e$ respectively, see Figure 9, 10 and 11. The heat gain from lights for a secondary school of 12.82 W/m^2 was slightly larger than hospital's 12.71 W/m^2. The internal heat gain from occupants was found to be higher for secondary school buildings, due to greater occupancy density. Secondary school's had an average density of 10.3 m^2/person, where hospitals averaged 25.63 m^2/person. The average ventilation rate for a secondary school was also higher than for hospitals, with an average ventilation rate of 1198.49 L/s as compared to 286.27 L/s. Finally, Table 5 provides the HVAC's lifetime MTCO2e GHG emissions per unit area floor area of various buildings for each of the 15 climate zones. This data can be used for annual emission estimates of similar building types.



(a)



(b)

Figure 8. (a) CO2e GHG emissions of hospital for all climate zones, and (b) percentage CO2e GHG emissions of Hospital for all climate zones

Table 5. MTCO2e GHG emissions per square meter of conditioned floor area for each climate zone

	CLIMATE ZONE														
Building Type	1A	2A	2B	3A	3B1	3B2	3C	4A	4B	4C	5A	5B	6A	6B	7
Medium Office	0.78	0.78	0.52	0.55	0.26	0.39	0.29	0.59	0.34	0.33	0.54	0.35	0.61	0.41	0.58
Small Office	1.04	0.95	0.68	0.66	0.32	0.48	0.30	0.73	0.48	0.40	0.78	0.52	0.86	0.60	0.86
Warehouse	0.87	0.27	0.22	0.14	0.04	0.13	0.05	0.17	0.13	0.10	0.26	0.20	0.34	0.27	0.41
Stand-Alone Retail	1.85	1.71	1.12	1.21	0.54	0.82	0.44	1.26	0.79	0.75	1.33	0.87	1.49	1.05	1.36
Primary School	1.08	0.95	0.63	0.59	0.27	0.47	0.30	0.63	0.39	0.31	0.63	0.40	0.73	0.48	0.71
Secondary School	0.83	0.83	0.60	0.69	0.31	0.55	0.42	0.82	0.57	0.58	0.92	0.65	1.10	0.82	1.19
Supermarket	1.09	1.47	1.14	1.35	0.71	1.09	1.01	1.60	1.25	1.30	1.81	1.46	2.06	1.79	2.31
Restaurant	4.71	4.50	2.97	3.43	1.40	2.70	1.74	3.80	2.64	2.48	4.07	2.92	4.59	3.45	4.82
Hospital	1.10	1.29	1.18	1.33	1.10	1.29	1.25	1.53	1.23	1.25	1.61	1.31	1.74	1.42	1.90
Small Hotel	1.39	1.29	0.89	0.95	0.58	0.73	0.51	0.89	0.63	0.49	0.88	0.61	0.98	0.63	0.96

4. Summary and conclusion

In conclusion, the opportunity to reduce GHG emissions in buildings' heating and cooling systems should focus first on operational energy efficiency gains. The results from this broad ranging study of commercial buildings confirmed the significance of operational energy use. It was found that emissions due to electricity and NG energy consumption were dominant, as emissions from M&P ranged from 1.9 – 4.2%, caused mainly from varying operation energy consumption. The regional emission factors for electricity were shown to cause significant emission variability, as buildings within the western interconnect had overall lower GHG emissions due to largely lower emissions factors. Finally, the local climate was found to influence individual building type emissions.

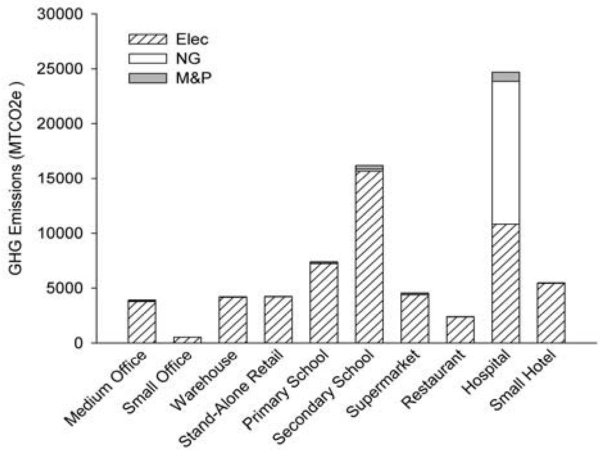


Figure 9. CO2e GHG emissions for all buildings in Miami (1A)

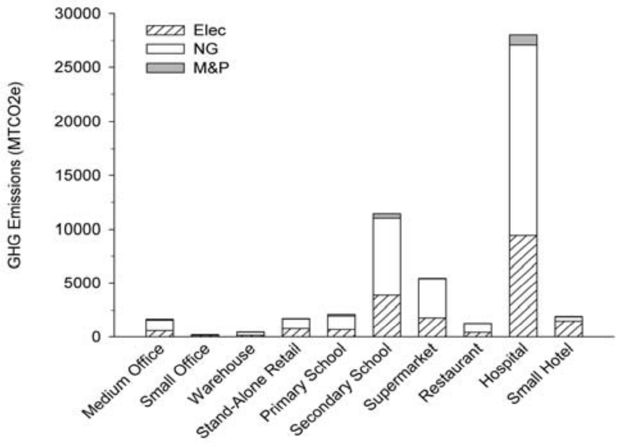


Figure 10. CO2e GHG emissions for all buildings in Seattle (4C)

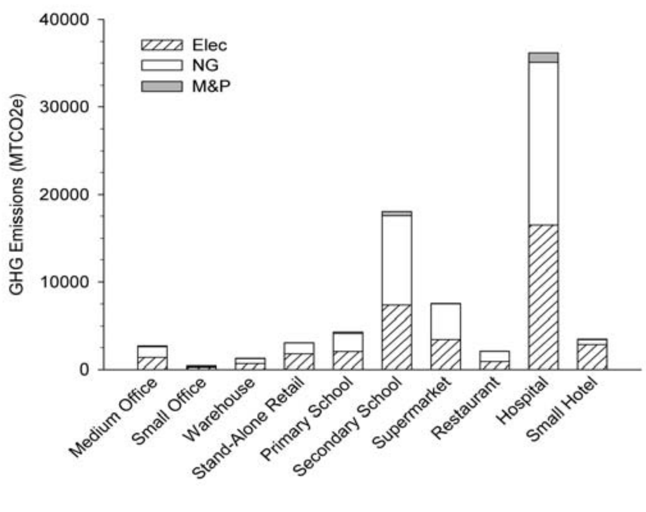


Figure 11. CO2e GHG emissions for all buildings in Chicago (5A)

References

[1] Adalberth, K., *Energy use during the life cycle of single unit dwellings: examples*, Building and Environment, 32(4), 321-329, 1997.

[2] Asif, M., Muneer, T. and Kelley, R., *Life cycle assessment: A case study of a dwelling home in Scotland.* Building and Environment, 42(3), 1391-1394, 2007.

[3] Scheuer, C., Keoleian, G.A., Reppe, P., *Life cycle energy and environmental performance of a new university building: modeling challenges and design implications*, Energy and Buildings, 35(10), 1049-1064, 2003.

[4] Thormark, C., *A low energy building in a life cycle - Its embodied energy, energy need for operation and recycling potential*, Building and Environment, 37(4), 429-435, 2002.

[5] Thormark, C., *The effect of material choice on the total energy need and recycling potential of a building*, Building and Environment, 41(8), 1019-1026, 2006.

[6] Mithraratne, N. and Vale, B., *Life cycle analysis model for New Zealand houses*, Building and Environment, 39(4), 483-492, 2004.
[7] Yohanis, Y.G. and Norton, B., *Life-cycle operational and embodied energy for a generic single-storey office building in the UK*, Energy, 27(1), 77-92, 2002.
[8] Cole, R.J. *Energy and greenhouse gas emissions associated with the construction of alternative structural systems*, Building and Environment, 34(3), 335-348, 1999.
[9] Fay, R., Treloar, G. and Iyer-Raniga, U., *Life-cycle Energy Analysis of Buildings: A Case Study*, Building Research & Information, 28(1), 31-41, 2000.
[10] Suzuki, M., and Oka, T., *Estimation of life cycle energy consumption and CO_2 emission of office buildings in Japan.* Energy and Buildings, 28(1), 33-41, 1998.
[11] Nyman, M and Simonson, C. J., *Life cycle assessment of residential ventilation units in a cold climate*, Building and Environment, 40(1), 15-27, 2005.
[12] Simonson, Carey J. and Nyman, Mikko, *Life-cycle assessment of air handling units with and without air-to-air energy exchangers*, ASHRAE Transactions, 110(1), 399-409, 2004.
[13] Rey, F.J., Martin-Gil, J., Velasco, E., Perez, D., Varela, F., Palomar, J.M. and Dorado, M.P., *Life cycle assessment and external environmental cost analysis of heat pumps*. Environmental Engineering Science, 21(5), 591-605, 2004.
[14] Shah Viral P.; Debella David C.; Ries Robert J., *Life cycle assessment of residential heating and cooling systems in four regions in the United States,* Energy & Buildings, v40, n4, pp.503-513, 2008.
[15] Sato, S., Watanabe, H., *LCA evaluation method for air-conditioner,* Matsushita Technical Journal, 45(3), 123-129, 1999.
[16] Deru M., *Moving toward better GHG calculations for buildings.* 2010 ASHRAE Annual Conference.
[17] Torcellini, R.; Deru, M.; Griffith, B.; Benne, K., *DOE Commercial Building Benchmark Models*, NREL/CP-550-43291, 2008. http://www.nrel.gov/docs/fy08osti/43291.pdf
[18] RSMeans 2002 Mechanical Cost Data. 25th Annual edition, RSMeans Company, Inc. Kingston, MA.
[19] Net Zero Energy Commercial Building Initiative, Office of Energy Efficiency and Renewable Energy (EERE), United States Department of Energy. http://www.eere.energy.gov/
[20] EIOLCA, Economic Input-Output Life Cycle Assessment website, Green Design Institute, Carnegie-Mellon University. http://www.eiolca.net/
[21] ASHRAE Standards, 90.1-2004 Energy Standards for Buildings Except Low-Rise Buildings, ASHRAE, Inc. http://www.ashrae.org/docLib/20060815_200661121930_347.pdf
[22] NERC, NERC Interconnection Map, North American Electric Reliability Corporation.
[23] Torcellini, R.; Deru, M., *Establishing standard source energy and emission factors for energy use in buildings*, Proceedings of the Energy Sustainability Conference 2007, 541-548, 2007, Proceedings of the Energy Sustainability Conference 2007.
[24] *Markups for Equipment Price Determination*, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. http://www1.eere.energy.gov/buildings/appliance_standards/commercial/pdfs/cuac_tsd_chp_7.pdf

Aik Jong Tan received his B.S. degree in mechanical engineering at the University of Arkansas, Fayetteville, Arkansas in 2007. His research focuses on energy and environmental impacts of energy systems in commercial buildings and industrial manufacturing, including the system-level analysis of greenhouse gas emissions and energy efficiency opportunities. Mr. Tan is a student member of the American Society of Mechanical Engineers and the American Society of Heating, Refrigerating, and Air-conditioning Engineers.
E-mail address: atan@uark.edu

Darin W. Nutter received his B.S. (1986) and M.S. (1988) in mechanical engineering at Oklahoma State University, Stillwater, Oklahoma. He received his Ph.D. in mechanical engineering at Texas A&M University, College Station, Texas in 1994. His research interests are encompassed within the broad area of energy systems. His background and recent focus has been on industrial manufacturing process energy conservation, fossil-fuel based greenhouse emissions, HVAC&R equipment, insulating materials, and high-performance buildings. He is the author of more than 40 technical publications. Dr. Nutter is a professional engineer and a member of the American Society of Mechanical Engineers and the American Society of Heating, Refrigerating, and Air-conditioning Engineers.
E-mail address: dnutter@uark.edu