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# Energy Consumption and Greenhouse Gas Emissions from Commercial and Manufacturing Sectors Specific Studies on HVAC Equipment and Dairy Processing

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# ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS FROM COMMERCIAL AND MANUFACTURING SECTORS

## SPECIFIC STUDIES ON HVAC EQUIPMENT AND DAIRY PROCESSING

# ENERGY CONSUMPTION AND GREENHOUSE GAS EMISSIONS FROM COMMERCIAL AND MANUFACTURING SECTORS
## SPECIFIC STUDIES ON HVAC EQUIPMENT AND DAIRY PROCESSING

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Mechanical Engineering

By

Aik Jong Tan
University of Arkansas
Bachelor of Science in Mechanical Engineering, 2007

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University of Arkansas

# ABSTRACT

Commercial and manufacturing sectors in United States consumed approximately 50% of the total End use energy in 2010. In 2009, 81.5% of the greenhouse gas (GHG) emitted in the United States was energy related. From the broad aspects of commercial and manufacturing sectors; two relatively narrow and specific topics, commercial building's HVAC equipment and dairy processing were chosen to increase the understanding of the energy use and GHG emission in these two sectors. Few published studies related to these two specific areas are available. The first study in this thesis discussed the energy use and GHG emissions by HVAC equipment in commercial buildings. The second study in this thesis discussed the energy use and GHG emissions of dairy processing plant with 4 production sequences, fluid milk, cream, whey and cottage cheese. The mass and energy balance of each individual unit operation in the sequence were studied and the total GHG emissions per unit of final product were found. Compared to natural gas (NG) use, the GHG emission from electricity use by commercial building's HVAC equipment is dominant. Furthermore, energy use and GHG emissions were also influenced by these factors, source emission factors, climate, building specifications, HVAC capacity and building location geographical influence. NG based unit operation in dairy processing plant were found to be the largest GHG emitter. The studies found component-level study is critical and necessary to better understand fossil fuel based energy use and GHG emissions impact. GHG emissions due to inefficiencies at the electric power generation origins are magnified at consumer end.

This thesis is approved for recommendation

to the Graduate Council.

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## LIST OF PUBLICATIONS

Tan, A. J. and Nutter, D.W., 2011, *$CO_2e$ emissions from HVAC equipment and lifetime operation for common U.S. building types,* International Journal of Energy And Environment, 2(3), pp. 415-426.
http://ieefoundation.org/ijee/vol2/issue3/IJEE_03_v2n3.pdf

Tan, A. J., Nutter, D.W., Milani, F., *GHG emissions and energy use from a multi-product dairy processing plant,* ASME 2011 Early Career Technical Conference Proceedings, March 31-April 2, 2011.
http://districts.asme.org/DistrictE/ECTCPapers/2011Papers/ECTCpaper-AR-AJTan.pdf

# 1. INTRODUCTION

Greenhouse gas (GHG) is a common household expression these days as the public is becoming increasingly aware of its direct relation to the effects of global warming and possible long term climate change. Since the advent of the industrial revolution, the demand for energy has increased at an alarming pace and the fuel that met these energy demands came largely from fossil fuel sources. The combustion of fossil fuel produces $CO_2$ which is the primary and significant component of GHG. A reduction in energy consumption is an important factor in GHG emissions reduction. A comprehensive understanding of GHG emissions associated with anthropogenic activities would provide valuable insight into energy consumption behavior, pattern and trends. As the cost of fuel and energy escalates at an alarming pace, the reduction in GHG emissions also translates into a tremendous energy cost savings. Therefore, an understanding of GHG and its relation to energy consumption is a critically important factor to the preservation of the environment, and the competitiveness of the nation's economy.

GHG are a group of several types of naturally occurring and anthropogenically produced gases. As its name implies, its presence in the atmosphere would induce a greenhouse effect in the earth's atmosphere. GHG have the ability to "capture" and "trap" the heat from sun light that enters the earth's atmosphere. It is believed that a "cause and effect" relationship exists between the GHG, the greenhouse effect, global warming and possible long term climate change. Not all the gases in the atmosphere are GHG. Only certain gases are classified and inventoried as GHG for the purpose of GHG emissions study. The United States Environmental Protection Agency considers Carbon Dioxide ($CO_2$), Methane ($CH_4$), Nitrous Oxide ($N_2O$), Hydroflurocarbons (HFC), Perfluorocarbons (PFC), Sulfur Hexafluoride ($SF_6$), Ozone ($O_3$) and water vapor as major greenhouse gases. Although water vapor and Ozone are classified as GHG, these gases are not included in the GHG inventory and emissions studies [1]. The greenhouse effect begins when sunlight consist of shorter wavelength ultra violet, visible light and near infrared in the form of solar radiation enter and travel through the atmosphere. A small portion of this incoming solar radiation is absorbed by the gases in the atmosphere but a large portion of it is absorbed by earth's surface. Earth's surface absorbs the heat energy and emits the longer wavelength infrared back into the air and warms the atmosphere. GHG molecules in the atmosphere absorb and re-radiate the infrared to all directions. The upward re-radiated infrared leaves the atmosphere and enter the outer space. The downward re-radiated infrared would further warm the lower atmosphere and is absorb by the earth's surface again. This repeated cycle of absorption and emission from earth's surface warms the lower atmosphere until equilibrium is achieved. Although some infrared radiation eventually leaves the atmosphere into space through the upward re-radiation, the majority of the infrared radiation remains inside the atmosphere. In short, the GHG molecules which posses the propensity to captures and traps the heat energy from solar radiation plays a critical role in retaining heat energy from solar radiation in the earth's atmosphere instead of allowing it to reflect completely back into outer space as shown in figure 1.

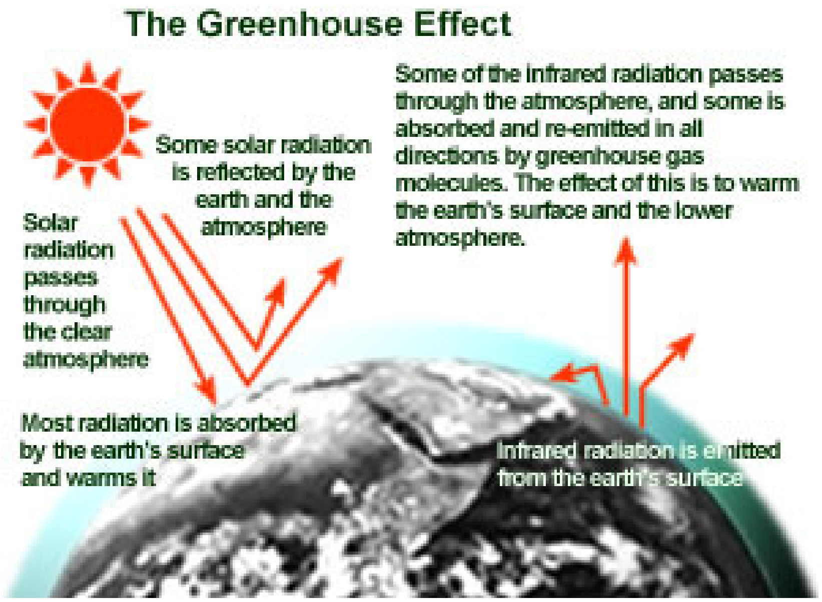


Figure 1, Greenhouse effect in Earth's atmosphere [2]

The ability to absorb energy varies with different types of GHG. In other words, GHG possess different "potency" in inducing the greenhouse effect and global warming in the atmosphere, depending on the type of gas. Carbon Dioxide Equivalent ($CO_2e$) is the international standard measurement adapted to compare a GHG's ability to induce global warming based upon their Global Warming Potential (GWP). Global Warming Potential (GWP) is defined as the cumulative radiative forcing effects of a gas over a specified time horizon resulting from the emission of a unit mass of gas relative to a reference gas [3]. Since $CO_2$ is the most abundant and important GHG, $CO_2$ is designated as the reference gas for making potency comparisons with all other GHG. $CO_2e$ is defined as the product of one million metric tons of a gas and GWP of a gas, as shown in equation 1 [4].

Equation 1:

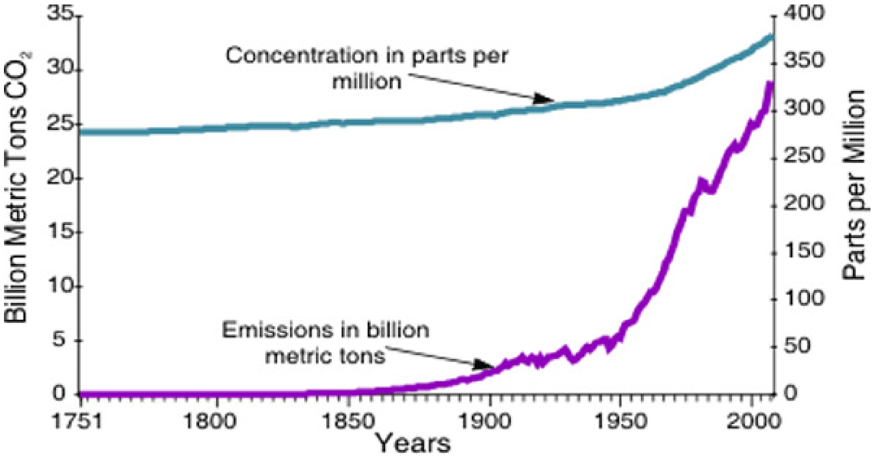
$$MMCO_2e = Million\ Metric\ Tons\ of Gas\ \times Global\ Warming\ Potential\ of\ Gas \quad [4]$$

Since GWP is different for each GHG, GHG with a higher GWP value has a larger Greenhouse effect even in smaller quantities. Table 1 shows the GWP values for different GHG.

Table 1, Global Warming Potential (GWP) Of Different GHG Over 100 Year Time Horizon [3]

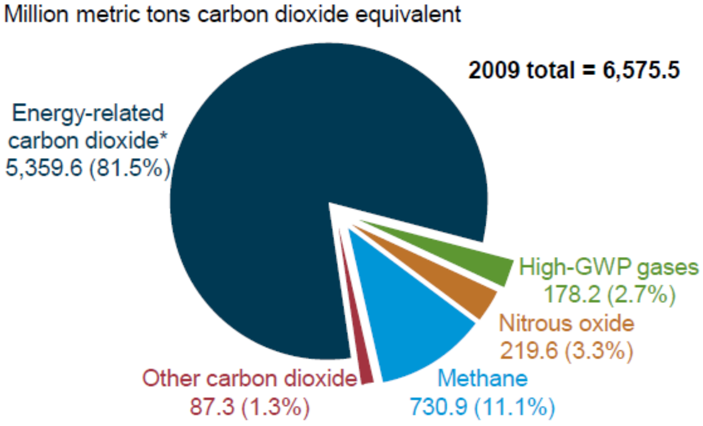
| GAS | GWP |
|---|---|
| Carbon Dioxide | 1 |
| Methane | 21 |
| Nitrogen Oxide | 310 |
| HFC-23 | 11,700 |
| HFC-125 | 2,800 |
| HFC-134a | 1,300 |
| HFC-143a | 3,800 |
| $CF_4$ | 6,500 |
| $C_2F_6$ | 9,200 |
| $C_4F_{10}$ | 7,000 |
| $SF_6$ | 23,900 |

The study of GHG and its possible effects began in the 19th century with the study and measurements of $CO_2$ content in the earth's atmosphere. French scientist Jean-Baptiste Fourier was the first to recognize the warming effects on the earth's surface due to the existence of certain atmospheric gases in 1827 [5]. In the 1860s, British scientist John Tyndall performed studies on infra-red radiation absorption by $CO_2$ gas and water. Tyndall suggested the decrease in atmospheric $CO_2$ concentration was a possible cause of the ice ages. Swedish scientist Svante Arrhenius suggested the doubling of $CO_2$ concentration in the atmosphere could possibly lead to a rise of the planet's surface temperature through greenhouse effects [5]. In 1938, British engineer Guy S. Callendar suggested the combustion of fossil fuel is contributing substantial amounts of $CO_2$ gas to the earth's atmosphere [5]. Statistical measurement of atmospheric $CO_2$ began in 1957; atmospheric $CO_2$ has continuously been measured since. This statistical atmospheric $CO_2$ measurement was initiated by Charles Keeling at Caltech in Pasadena, California as a study on the equilibrium of carbonate in surface waters, limestone and atmospheric $CO_2$. More importantly, Keeling proved the level of $CO_2$ in the earth's atmosphere was steadily rising [6]. During the same period, Gilbert Plass identified the ability of $CO_2$ gas to absorb the energy of sunlight in the 15 micrometer wavelength band. Plass also attributed the warming of the earth's surface, to this energy absorption, as it created a thermal blanket around the atmosphere [5]. Since the most important and most abundantly tracked GHG is $CO_2$, atmospheric $CO_2$ level tracking began in the late 1950s. The Mauna Loa tracking station in Hawaii was established by Keeling in 1958. It is the oldest and has the longest $CO_2$ tracking record with over 50 years of atmospheric $CO_2$ levels recorded [6]. The tracking records indicate that the level of $CO_2$ concentration has been steadily increasing since the turn of the 20th century as indicated in Figure 1 below. According to the US Energy Information Administration, in 2009, 81.5% of the GHG emitted in the US is $CO_2$ and was energy related [7], as shown in Figure 2. Three quarters of GHG emissions are from anthropogenic activities in the past twenty years [8]. Though the relation between global warming and $CO_2$ emissions remains controversial, many studies suggest a close relationship between the two, and the major contributor of $CO_2$ emissions is from anthropogenic activities, i.e. GHG emissions generated by humans.



Source: Oak Ridge National Laboratory, Carbon Dioxide Information Analysis Center.

Figure 1, Historical $CO_2$ emissions and concentrations [8]



*Adjusted by removing emissions from bunker fuels and adding emissions from U.S. Territories.

Figure 2, 2009 Greenhouse Emissions in the Unites States in 2009 [7]

The Energy Information Administration has categorized energy use in the United States into 4 end use sectors; residential, commercial, industrial and transportation. The percentage usage for 2010 is as shown in figure 3. In 2010, the United States Energy Information Administration estimated total energy consumption by sectors as; residential, 22,153 trillion BTU; Commercial sector, 18,205 trillion BTU; Industrial, 30,139 trillion BTU; and Transportation, 27,507 trillion BTU [9]. The total end-use energy was 98,003 trillion BTU. In other words, the approximated percentage of each sector was as follows: Residential, 23%, Commercial, 19%, Industrial, 31% and Transportation, 28%, as shown in Figure 3. Each of these sectors represents roughly a quarter of all energy produced in the United States. Looking closely at commercial and industrial sectors, the total energy consumed is close to 50% of all energy produced. An understanding of how energy is consumed within these two separate sectors is needed in order to further reduce energy use.

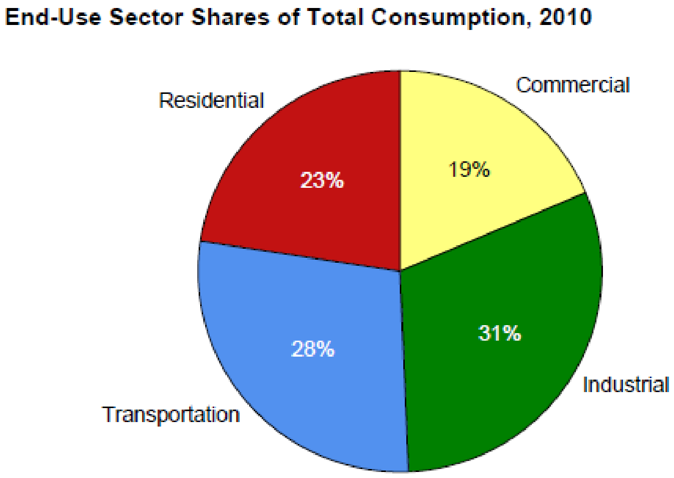


Figure 3, Energy end-use by 4 different sectors in the United States in 2010 [10]

The overall objective of the studies in this thesis was to increase the understanding of GHG emissions related to both commercial and industrial sectors. Since these two sectors are considerably large and encompass many aspects, it is impossible to investigate every industry. If we focus on narrow topics, it would lead to a fairly well understanding of the energy consumption and GHG emissions behavior. With a better understanding of the processes and components that are large energy consumers and emitters of GHG, improvements in efficiency to reduce energy use and GHG emissions can be better targeted. Two specific studies on HVAC equipment in commercial buildings (chapter 2) and dairy processing (chapter 3) plant were performed. Finally, chapter 4 provides a brief discussion on the overarching conclusion drawn from these studies.

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[9] Table 2.1a Energy Consumption Estimates by Sector, Selected Years, 1949-2010, Annual Energy Review 2010, United States Energy Administration, pp.40, October 2011.
http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf

[10] Figure 2.1a Energy Consumption Estimates by Sector Overview, Annual Energy Review 2010, United States Energy Administration, p.38.
http://www.eia.gov/totalenergy/data/annual/pdf/aer.pdf

# 2. $CO_2e$ EMISSIONS FROM HVAC EQUIPMENT AND LIFETIME OPERATION FOR COMMON U.S. BUILDING TYPES

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

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## 2.1 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.

## 2.2 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.

## 2.3 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.

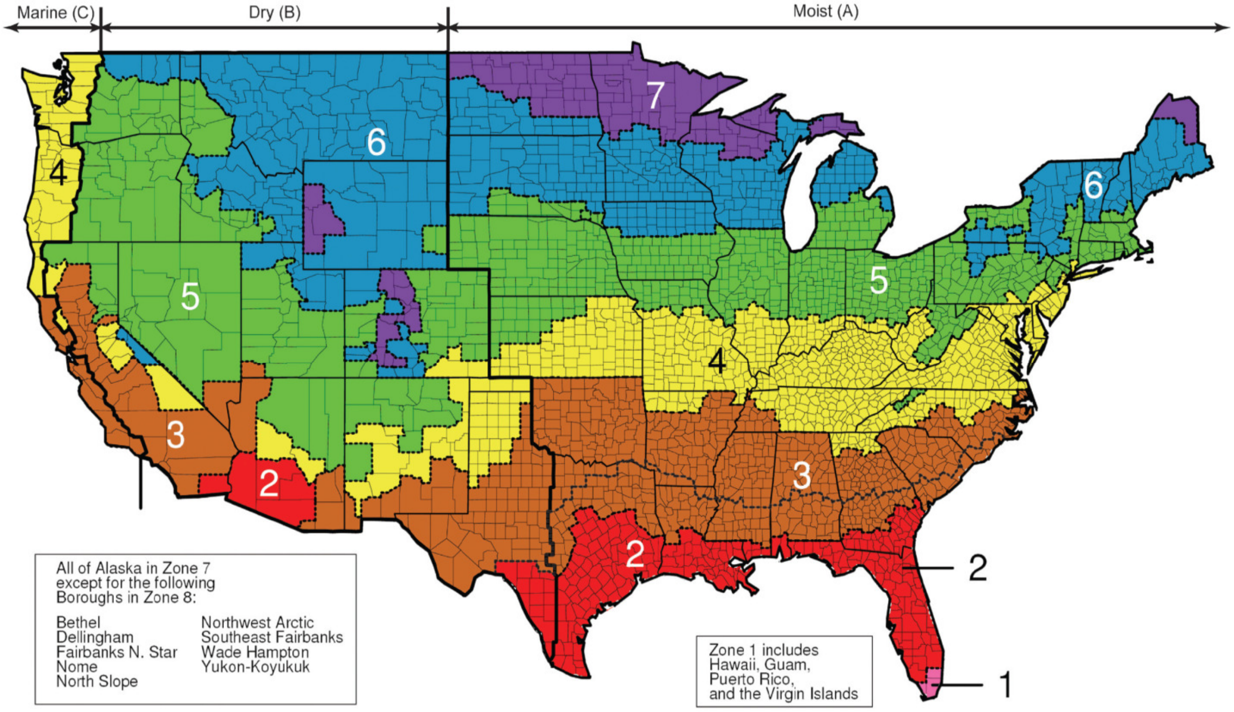

Figure 1. The Climatic Zone in the United States [21]

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 |

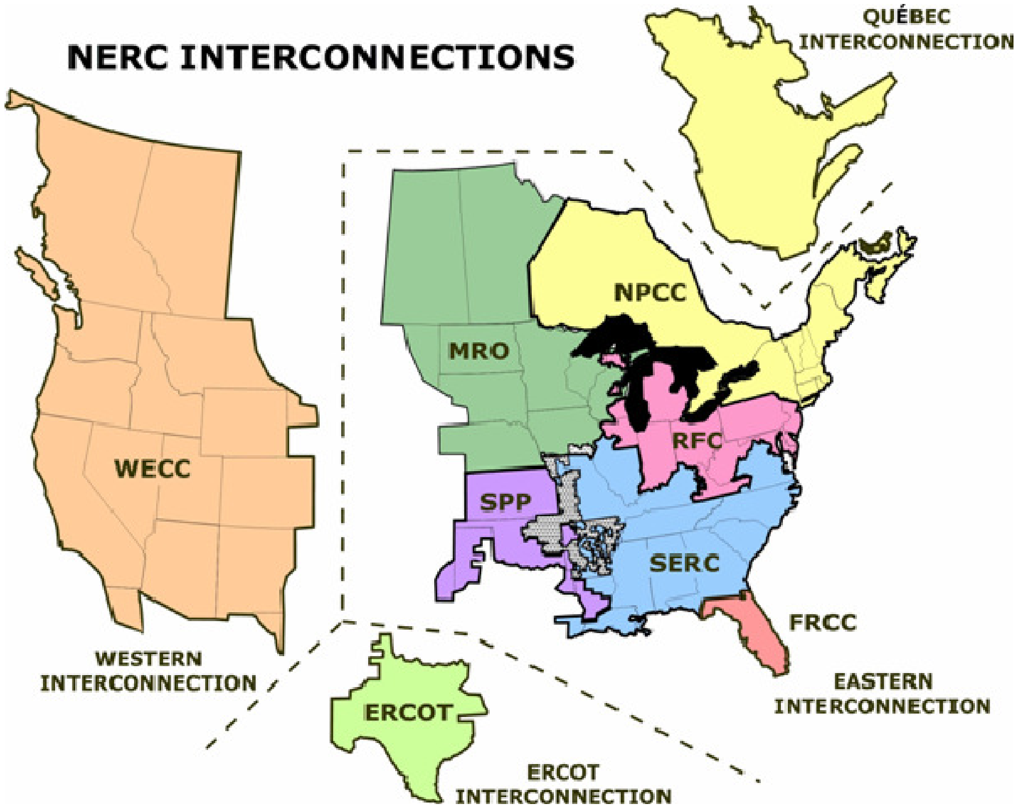

Figure 2. NERC Interconnection of North America [22]

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. 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.

Table 2. eGRID emission factors [23]

| eGRID Region | a. Combined pre-combustion and combustion emission factor (kg$CO_2$e/kWh) | b. Transmission and Distribution (T&D) Losses (%) | a + b Total regional $CO_2$e emission rate (kg$CO_2$e/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 $CO_2$e/unit) | b. Combustion emission rate (kg $CO_2$e/unit) | a + b Combined pre-combustion and combustion emission factors (kg $CO_2$e/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.

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 |

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.

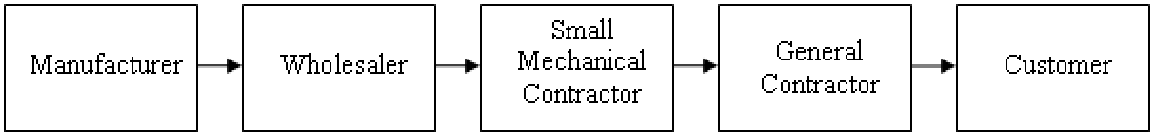

Figure 3. Flowchart of the standard price markup for HVAC equipment

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.

## 2.4 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%.

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 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).

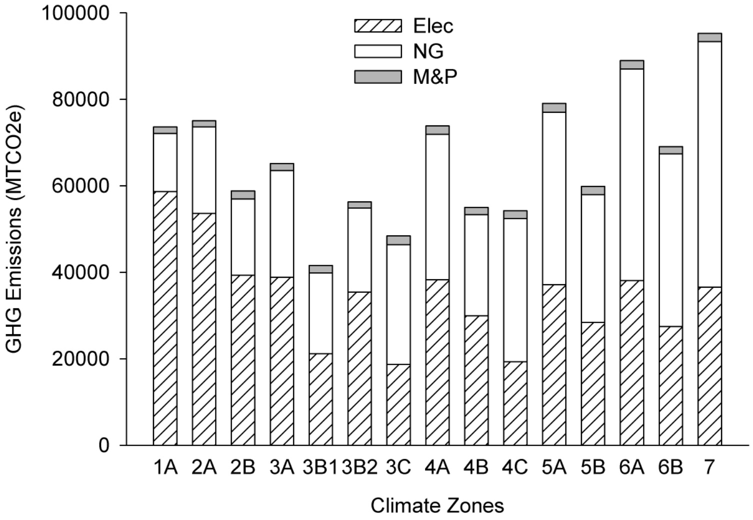

Figure 4(a). Total $CO_2$e GHG emissions for all buildings within each climate zone

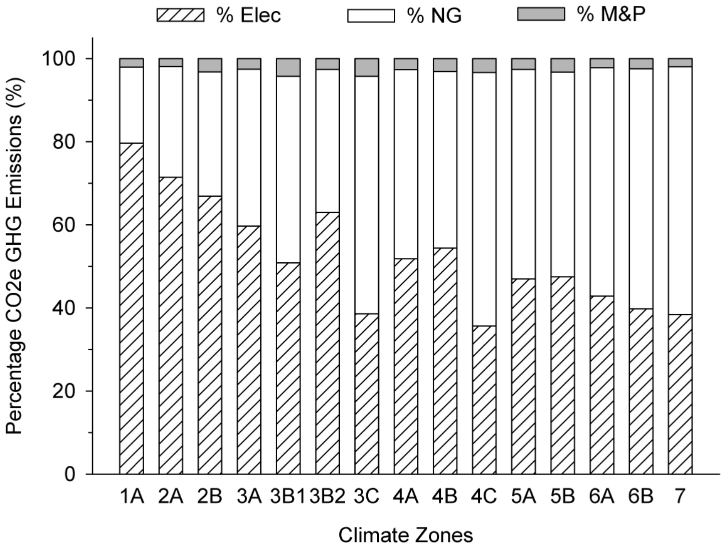

Figure 4(b). Percentage total $CO_2$e GHG emissions for all buildings within each climate zone

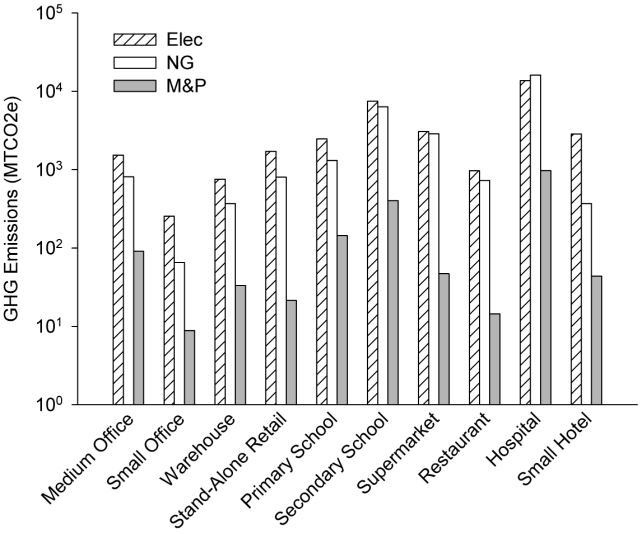

Figure 4(c). Average $CO_2e$ GHG emissions and sources for each building type across all climate zones

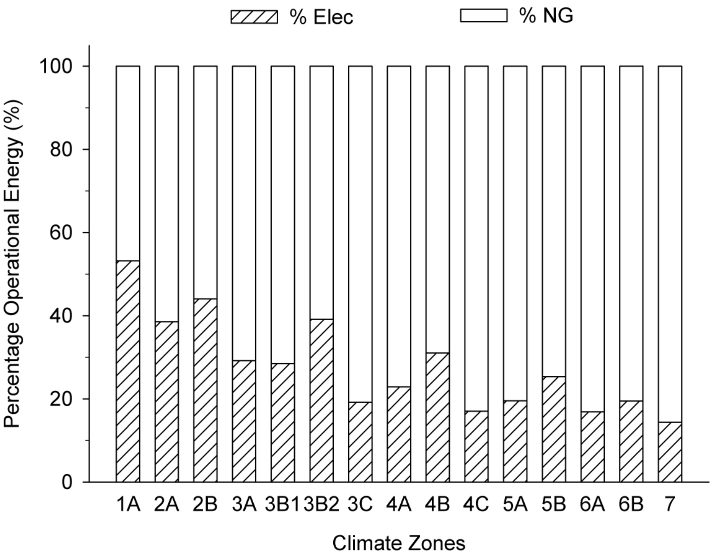

Figure 5(a), Percentage total operational site energy for all buildings within each climate zone

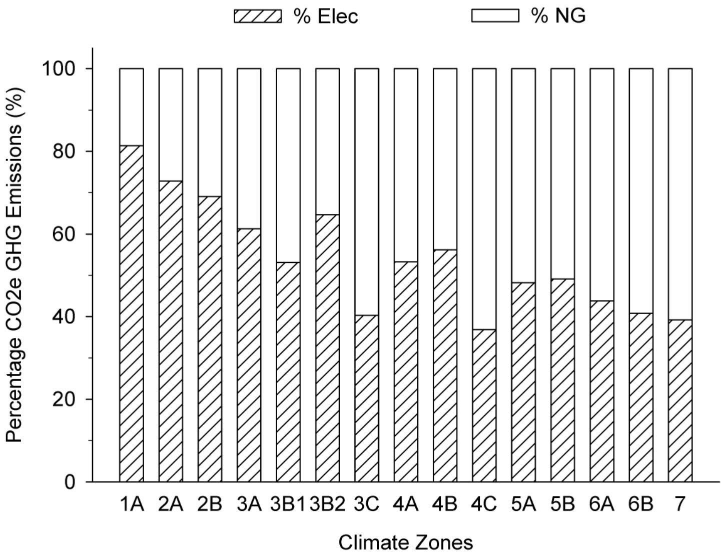

Figure 5(b). Percentage $CO_2e$ emissions of operational energy for buildings within each climate zone

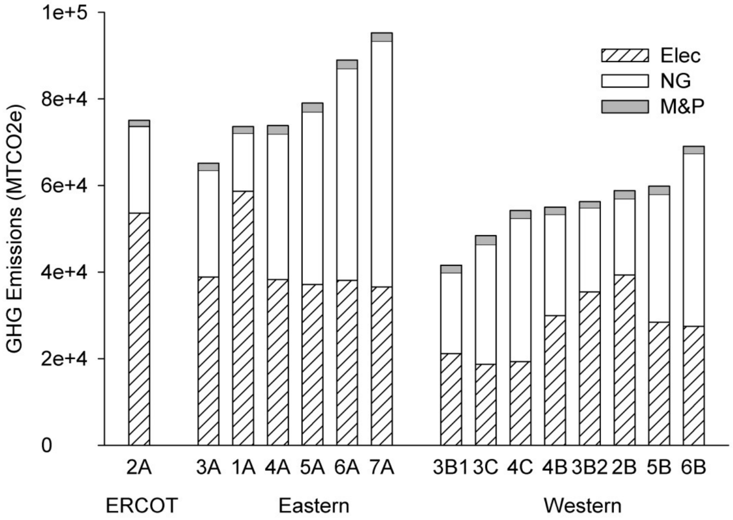

Figure 6. GHG emissions comparison of ERCOT, Eastern and Western Interconnects

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 12.71 $W/m^2$ and 23.19 $W/m^2$, respectively; likewise, lighting and plug loads were 10.76 $W/m^2$ and 8.07 $w/m^2$, respectively for medium office buildings.

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.

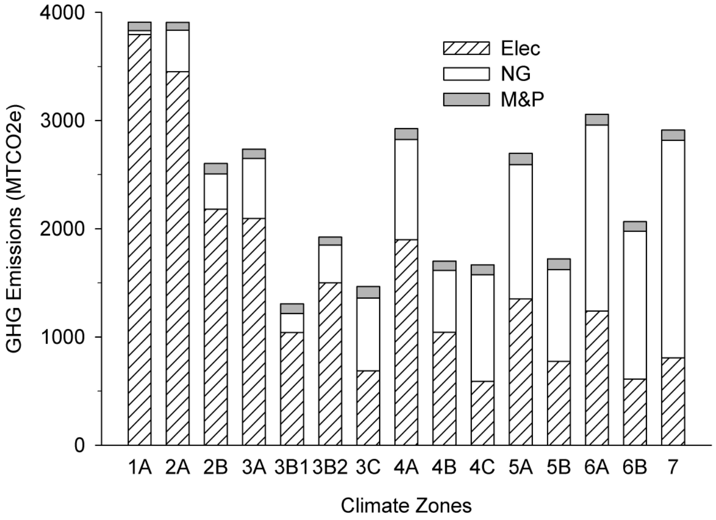

Figure 7(a). $CO_2e$ GHG emissions of medium office for all climate zones

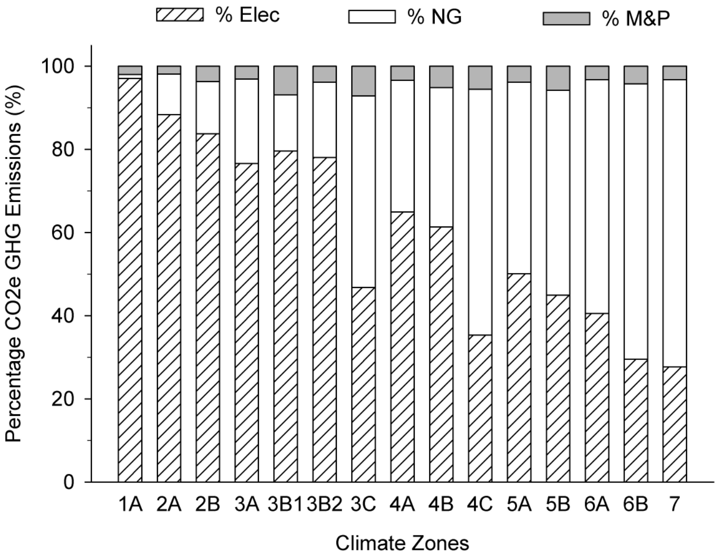

Figure 7(b). Percentage $CO_2e$ GHG emissions of medium office for all climate zones

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 by hospitals during December and January were 85 $MTCO_2e$ and 87 $MTCO_2e$, during July and August were 38 $MTCO_2e$ and 36 $MTCO_2e$. For Duluth (7), during December and January were 122 $MTCO_2e$ and 129 $MTCO_2e$, during July and August were both 45 $MTCO_2e$.

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.

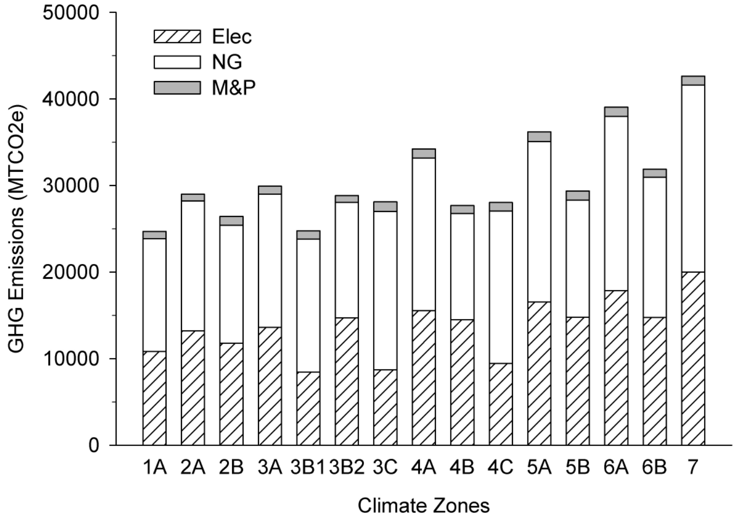

Figure 8(a). $CO_2e$ GHG emissions of hospital for all climate zones

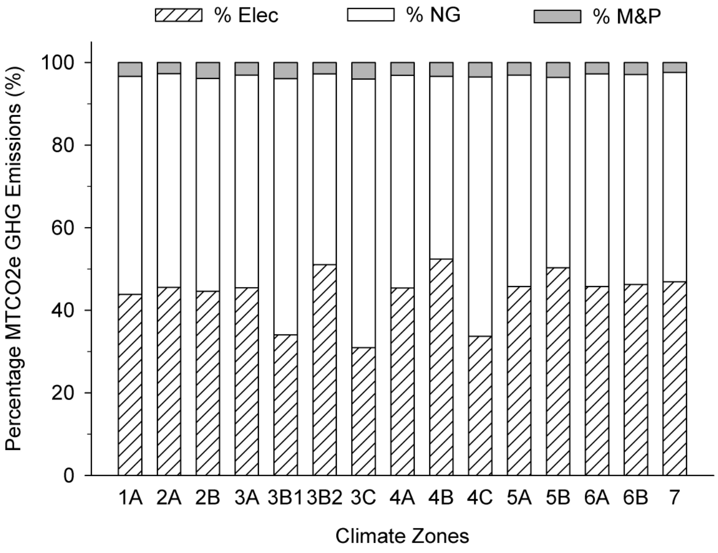

Figure 8(b). Percentage $CO_2e$ GHG emissions of Hospital for all climate zones

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 304% 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 13.13 $W/m^2$ 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 1208.3 L/s as compared to 637.3 L/s. Finally, Table 5 provides the HVAC's lifetime $MTCO_2e$ 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.

Table 5. $MTCO_2e$ GHG emissions per square meter of conditioned floor area for each climate zone

| **BUILDING TYPE** | **CLIMATE ZONE** | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 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 |

## 2.5 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.

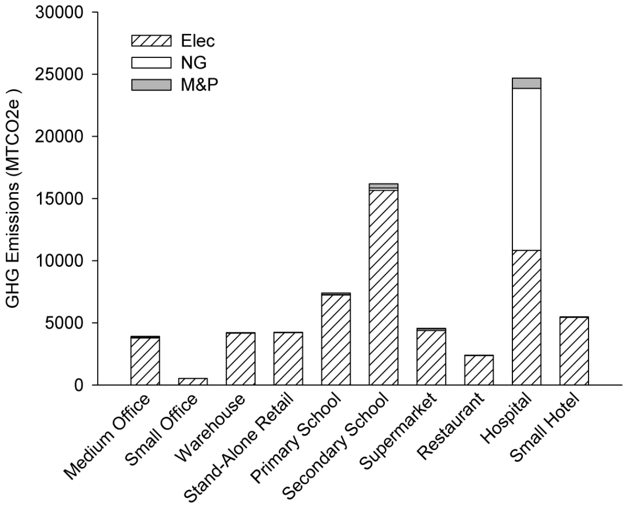

Figure 9. $CO_2e$ GHG emissions for all buildings in Miami (1A)

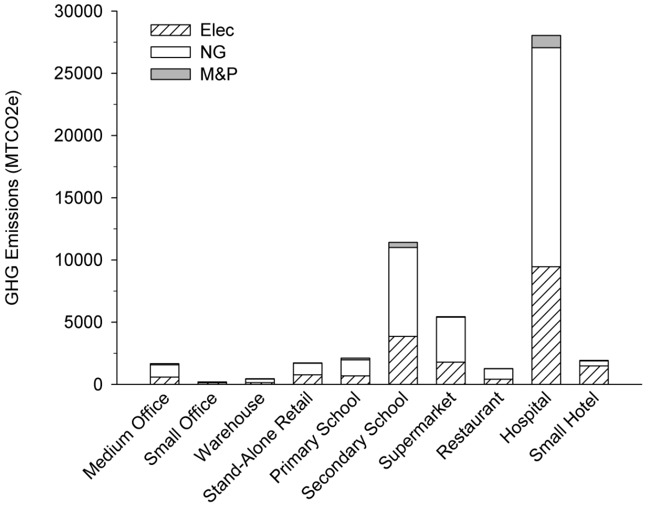

Figure 10. $CO_2e$ GHG emissions for all buildings in Seattle (4C)

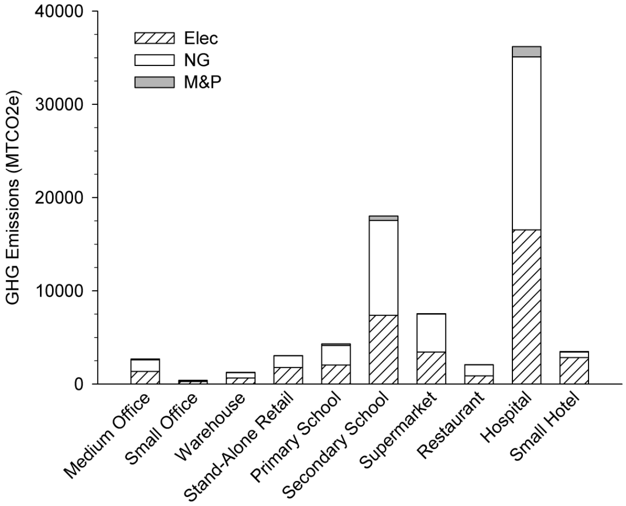

Figure 11. $CO_2e$ GHG emissions for all buildings in Chicago (5A)

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# 3. GHG EMISSIONS AND ENERGY USE FROM A MULTI-PRODUCT DAIRY PROCESSING PLANT

**2011 ECTC Proceedings**

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## GHG EMISSIONS AND ENERGY USE FROM A MULTI-PRODUCT DAIRY PROCESSING PLANT

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## 3.1 ABSTRACT

The dairy industry continually seeks to better understand both the energy use and associated greenhouse gas (GHG) emissions in all aspects of their business, including fluid milk, cheese, whey, yogurt, and many other products. A recently completed study showed that agriculture and producer unit processes were the largest contributors of GHG emissions; however, milk processing was not insignificant in terms of both energy and GHGs. This paper uses an available detailed process flow diagram, along with mass and energy balance data, to evaluate GHG emissions of a multi-product (fluid milk, cream, cottage cheese, and whey powder) dairy processing plant at the industrial unit operation level. Results from this study found the cooking process within the cottage cheese and whey sequence to be the largest emitter, followed by pasteurization, cold storage, packaging and CIP processes. Opportunities for GHG reductions, through improved both natural gas and electric energy efficiency, were also discussed.

## 3.2 INTRODUCTION AND BACKGROUND

Milk and dairy products are one of the most important foods for human consumption. Raw milk is processed before it can be safely consumed since it can be a source of bacterial growth. Even stored near room temperature, fresh raw milk collected from a dairy farm can experience exponential bacterial growth within just a few hours. Milk processing is necessary and a fairly energy intensive process that requires multiple steps to transform raw milk into various type of dairy products – skim milk, 1% milk, 2% milk, whole milk, cream, cheese, whey and others. In 2005, the production of raw milk and cheese was 645 million metric tons globally

[1]. In comparison with the European dairy producing countries of Great Britain, Netherlands, Denmark and Norway, the US processes much more raw milk into consumable fluid milk, annually amounting to $25x10^9$ kg [2]. The US is followed by Great Britain at $8.5x10^9$ kg and the Netherlands at $2.2x10^9$ kg per year [1]. Total US production of raw milk in 2009 was over $85x10^9$ kg [3].

A literature review found that very few studies or published research are available in the public domain, specifically associated with energy usage and GHG emissions from milk/dairy processing within the United States. Xu et al. [4] and Xu and Flapper [1] include some US dairy processing energy use compared to other dairy processing countries. One of only a few US studies was recently performed by the University of Arkansas and Michigan Technological University to determine the carbon footprint of US fluid milk. The study found the overall aggregate total cradle-to-grave carbon footprint in 2007 was 2.05 kg $CO_2e$ per kg milk consumed. As part of the study, the energy-related gate-to-gate carbon footprint of fluid milk processing and packaging was found to be 0.096 kg $CO_2e$ per kg of packaged milk [5]. Without more refined information, it is difficult to explore energy conservation and GHG emissions reduction opportunities. Reduction in energy use would lead to cost reductions and, therefore, reduce dairy food prices in the long term. This paper explores the energy use and associated GHG emissions associated with the individual unit operations in processing fluid milk into four dairy products.

Brown et al. of Drexel University published a study, supported by the US Department of Energy, in an effort to better understand the energy use of common industrial processes. The results were published in the book entitled *Energy Analysis of 108 industrial Processes* [6]. The publication provided aggregate mass and energy balances of individual component processes (i.e., unit operations) for many common industrial products. The study draws information from industrial process flow diagrams, industrial consultants and census of manufactures data. Furthermore, the energy and mass balances are accounted on a per unit mass basis. Temperature, pressure, fuel requirements, thermal efficiency and other critical operating parameters are also included. One such set of process flow diagrams, unit operations, and associated mass/energy balances was used in this study – categorized as fluid milk; however, four products are described: fluid milk, cream, cottage cheese, and whey powder. No further product descriptions were provided. Figures 1 provides the specific process flow diagram for the products and each product's unit operations. Figure 2 gives a schematic for a generic unit operation. Also, Table 1 gives the mass and energy balance input data for unit operations 1-20.

## 3.3 METHODOLOGY

For milk processing, as shown in the unit operation flow diagram (Figure 1), 476 g (1.05 lbm) of raw milk enters the 'plant' and the final processed products exiting are 8.16 g (0.018 lbm) of cottage cheese, 4.54 g (0.01 lbm) of whey powder, 453 g (1.0 lbm) of fluid milk, and 13.6 g (0.03 lbm) of cream. This study computed the GHG emissions (in g $CO_2$e per kg of final product) for each product and for each unit operation. Cottage cheese production followed unit operation sequence 1-3, 11-14, and 16-18; whey production followed unit operation sequence 1-

3 and 11-15; fluid milk production followed unit operation sequence 1-10; and cream followed 1-4, 6, and 8-10.

The procedure for determining the GHG emissions included:

1. Determining the unit operation sequence for each product
2. Interpreting the inlet and outlet energy and mass flows for each unit operation
3. Converting secondary energy sources (steam, chilled water, and refrigeration) into their according 'primary energy' source of electricity or heating fuel (assumed to be natural gas)
4. For each unit operation, summing the inlet energies for each primary energy (electricity and natural gas)
5. Computing the total GHG emissions for each unit operation by multiplying the appropriate emission factor ($CO_2$e/unit energy) and the given unit operation's primary energy total (determined in #4 above).
6. Computing the per unit value emissions by dividing total GHG emissions by the mass of each final product produced. Note that three of the four final products have the same mass as their respective inlet flows; however, the final product mass for the whey is 0.4 g (0.001 lbm) as opposed to 0.9 g (0.002 lbm) at the inlet of the whey production stream. The difference is due to the evaporation of water from the liquid whey within the dryer (unit operation #15).
7. Analyze resulting emissions.

Boiler energy use (unit operation #20) was split into two steam use categories: process heat (called 'boiler-fuel-process') and non-process (called 'boiler-fuel-other'). Non-process steam use was for space heating (SH) and clean-in-place (CIP) systems. Boiler-fuel-process energy use calculations were based on the provided steam and condensate mass flows, 121 °C (250 °F) saturated steam, and an assumed open atmosphere flash tank. Remaining boiler energy use was allocated to the boiler-fuel-other category. It was found that 49% of NG was consumed by process heating and the remaining 51% for the boiler-fuel-other category. Similarly, refrigeration energy use (unit operation #19) was assumed to be electricity-based and was allocated to unit operations according to each fraction of total.

Once the quantities of electrical and natural gas energy use by each unit operation were established, then the associated emissions were calculated with source emission factors. The electricity source emission factor used was 0.244 g $CO_2$e per BTU, the North American Electric Reliability Corporation (NERC) Interconnection national average value. Other values such as the three regional NERC interconnect values or the 27 eGrid sub-region NERC values could be used if a more specific US location is of interest. The natural gas source emission factor used was 0.06642g $CO_2$e per BTU. [7]

## 3.4 UNIT OPERATION DISCRIPTIONS

Processing raw milk to dairy products involves the unit operations/processes described below.

**Receiving and Storage.** Milk is produced and chilled at the farm and then transported by large tanker trucks to the dairy processing plant. The raw milk is graded, weighted, and sampled. After quality testing, the raw milk is transferred by pump from the tanker to the plant's large (50k-100k liter) refrigerated storage silos, and then the tanker is cleaned and disinfected. The milk is quickly chilled to below 4 °C and constantly monitored. Also, the milk inside the silos is gently agitated to prevent cream separation. Typically, the milk processing facility will process all incoming milk within 24 hours of arrival.

**Clarification and Standardization.** Clarification is the process where the solid impurities in the milk such as dirt, bacteria sediments, sludge, etc. are removed with a centrifugal clarifier. The collected solid impurities are removed from the centrifugal clarifier on a continuous basis. After clarification, the milk is standardized, in which the fat and cream content of the milk is adjusted precisely to a specified value.

**Separation.** In the separation unit operation, skim milk is separated from the raw milk, resulting in two product streams, low/no fat content skim milk and a high-fat/milk solids milk and cream mixture. The process flow diagram in Figure 1 shows cold milk separation for simplicity; however, the predominant practice in industry is to separate milk after the regeneration section of the pasteurizer. The net effect upon resource use and outputs is unchanged.

**Pasteurization.** This is the famous sterilization process discovered by Louis Pasteur. It is defined as "any heat treatment of milk which secures the certain destruction of tubercle bacillus (T.B.) without markedly affecting the physical and chemical properties of the milk" [7]. There are different techniques of pasteurization – batch and continuous. The pasteurization method can be further differentiated into High Temperature Short Time (HTST), Low temperature Long Time (LTLT) and Ultra high Temperature (UHT), depending on the desired final product and shelf life expectancy.

**Homogenization.** Raw milk is an emulsion mixture of fat globules, oil, and water. If it remained stationary over a period of time, the large fat globules separate and rise to the surface of the milk as a layer of cream. Homogenization is a mechanical process in which milk is passed under pressure through a small orifice or passageway where the size of the fat globules is significantly reduced, reducing the fat globules' tendency of separation from the milk as cream.

**Pasteurizing Cooling.** After the pasteurization process, the thermally treated milk, destined for fluid milk and cream products, is cooled back to 4 °C again through a chilled water heat exchanger. Prior to cooling, the heat from pasteurized milk is typically used to pre-heat incoming raw milk entering the pasteurizer, through regenerative heat recovery. When cheese making is desired, milk after the pasteurization process is cooled to temperatures typically needed for beneficial dairy bacteria (culture) growth at 30-35 °C.

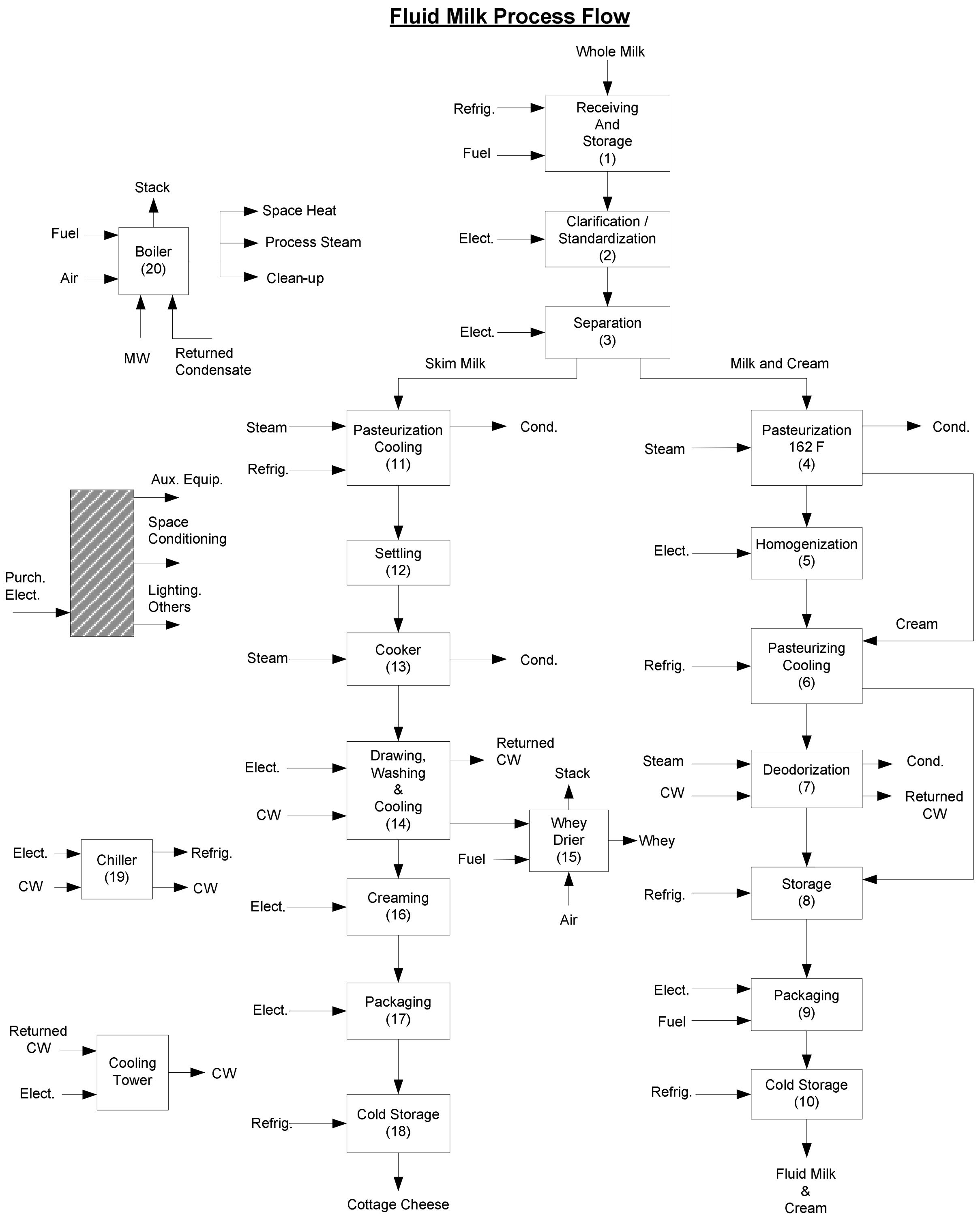

Figure 1. Flow diagram of multi-product dairy processing plant [6].

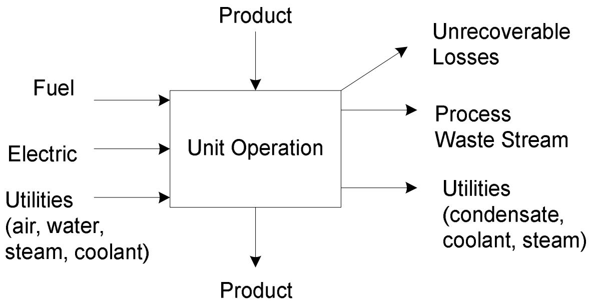

Figure 2. Schematic of a generic unit operation (or process) [6].

Table 1. Heat and mass balance data for individual unit operations 1-20. Note that refrigeration, steam, and chilled water inputs have been converted to their source energy inputs, either fuel or electricity.

| **Unit Operation** | | | **Material Inlet** | | | **Energy Inlet** | |
|---|---|---|---|---|---|---|---|
| **No.** | **Description** | **Temp, C (F)** | **Flow** | **Temp, C (F)** | **Mass, Kg (lbm)** | **Fuel, kJ (BTU)** | **Electricity, kJ (BTU)** |
| 1 | Receiving/ Storage | 4.4 (40) | Milk | 4.4 (40) | 0.476 (1.050) | 10.6 (10.0) | 8.1 (7.7) |
| 2 | Standard & Holding | 8.9 (48) | Milk | 4.4 (40) | 0.476 (1.050) | | 7.5 (7.1) |
| 3 | Separator | 10 (50) | Milk | 8.9 (48) | 0.476 (1.050) | | 15.9 (15.1) |
| 4 | Pasteurization | 72.8 (163) | Milk | 10.0 (50) | 0.454 (1.000) | 160.9 (152.5) | |
| | | | Cream | 10.0 (50) | 0.014 (0.030) | | |
| 5 | Homogenization | 37.8 (100) | Milk | 37.8 (100) | 0.454 (1.000) | | 9.1 (8.6) |
| 6 | Cooling | 0.6 (33) | Milk | 37.8 (100) | 0.454 (1.000) | | 39 (37.0) |
| | | | Cream | 37.9 (100) | 0.014 (0.030) | | |
| 7 | Deodorization | 3.3 (38) | Milk | 0.6 (33) | 0.454 (1.000) | 44.1 (41.8) | |
| 8 | Storage | 3.3 (38) | Milk | 3.3 (38) | 0.454 (1.000) | | 4.1 (3.9) |
| | | | Cream | 0.6 (33) | 0.014 (0.030) | | |
| 9 | Package | 3.3 (38) | Milk | 3.3 (38) | 0.454 (1.000) | 12.7 (12) | 47.7 (45.2) |
| | | | Cream | 3.3 (38) | 0.014 (0.030) | | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 10 | Cold Storage | 3.3 (38) | Milk | 3.3 (38) | 0.454 (1.000) | | 8.2 (7.7) |
| | | | Cream | 3.3 (38) | 0.014 (0.030) | | |
| 11 | Pasteurization | 72.9 (163) | Skim Milk | 10.0 (50) | 0.009 (0.020) | 3.3 (3.1) | 0.8 (0.7) |
| 12 | Settling | 3.3 (38) | Skim Milk | 0.6 (33) | 0.009 (0.020) | | |
| 13 | Cooker | 100.0 (212) | Skim Milk | 3.3 (38) | 0.009 (0.020) | 72.7 (68.9) | |
| 14 | Drawing/ Washing/ Cooling | 26.7 (80) | Skim Milk | 100.0 (212) | 0.009 (0.020) | | 2.0 (1.9) |
| 15 | Dryer | 82.2 (180) | Whey In | 26.7 (80) | 0.001 (0.002) | 3.2 (3.0) | |
| 16 | Creaming | 23.9 (75) | Skim Milk | 26.7 (80) | 0.008 (0.018) | | 1.8 (1.7) |
| 17 | Packaging | 23.9 (75) | Cottage Ch | 23.9 (75) | 0.008 (0.018) | | 0.84 (0.8) |
| 18 | Cold Storage | 3.3 (38) | Cottage Ch | 23.9 (75) | 0.008 (0.018) | | 3.1 (2.9) |
| 19 | Refrigeration | -28.9 (-20) | CW In | 23.9 (75) | 3.629 (8.000) | | 63.3 (60)* |
| 20 | Boiler | 121.1 (250) | Condensate | 82.2 (180) | 0.041 (0.090) | | |
| | | | Make Up | 23.9 (75) | 0.087 (0.191) | | |
| | | | Fuel - Process | | | 287 (272) | |
| | | | Fuel - Other | | | 298.6 (283)* | |

* These energies have been portioned to the actual unit operation (1-18) of use. Both are shown here for reference only.

**Deodorization.** Milk from animal tends to have odor that needs to be eliminated. In some systems, the odor is removed through a vacuum process that sufficiently removes the odor Milk is heated with steam and then flashed in a vessel to remove the odor giving gases.

**Storage.** The intermediate dairy product must be refrigerated and stored in a vessel at temperature below 4 °C to prevent bacterial growth.

**Packaging.** There are several methods to package dairy products based on the reusability of the container and packaging material. Examples of packaging materials include high density polyethylene (HDPE), low density polyethylene (LDPE), Polyethylene terephthalate (PET), paperboard, and glass. Whey powder can be stored in lined paper bags. For single service containers, examples are paperboard cartons, pouches, plastic bottles and bag-in-the-box.

**Cold Storage.** The final dairy product must be refrigerated and stored at temperature below 4 °C to prevent bacterial growth. At this unit operation/process, the final dairy product is ready to be shipped to distribution centers or retail stores.

**Settling.** Cottage cheese settling is primarily done with acid produced from the lactic acid producing bacteria added as culture. As the pH decreases from an initial value of 6.65 in fresh milk to a value of the finished curd of about 4.6, the casein protein will gel into the curd. A small amount of rennet is added to increase slightly curd firmness and consumer desirability. The coagulating process is complete when all the liquid milk has transformed into solid milk gel. The continuous gel throughout the vat, or coagulum, is then cut into smaller pieces. Cutting and cooking the curds allows the whey to be released from within the curd.

**Cooker.** In the cooker, the soft curd is heated up to increase the contract rate at which the curd squeezes out the whey. Cooking does not increase residual bacteria growth still inside the curd as the low pH prevents that growth. The combination of a settling vat and a cooker into one unit is pervasive in the industry.

**Drawing, Washing, and Cooling.** After the cooking process, the curd enters the drawing, washing, and cooling process. Liquid whey is continually drained from the curd. The curd is then washed several times to reduce the temperature and remove the residual liquid whey content. As the curd cools, it also shrinks and becomes firmer. Then, the water is drained from the curd and the curd is ready for the creaming process.

**Whey Dryer.** Before liquid whey is transfer to an evaporative dryer where liquid water is removed, the whey needs to be cooled and held for some time to allow the lactose to form into a stable and non-hygroscopic form. Due to the high acid content, proprietary methods are used in the drying of cottage cheese whey as compared to other cheese whey. There are several methods to separate liquid water from whey depending on the type of product desired. One way of drying whey is to feed the whey mixture into a vertical drying chamber and dried using heated air.

**Creaming.** In the creaming process, cream and salt are added to the curd. The amount of cream addition depends on the type of cottage cheese being produced.

## 3.5 RESULTS AND DISCUSSION

Figures 3-6 show individual results for each dairy product. Cottage cheese (Figure 3) and whey powder (Figure 4) production were found to have the highest emissions per unit mass of final product, 840 and 1,311 g $CO_2$e/kg of product, respectively. Natural gas consumption from steam use in the cooking unit operation (#13) was the primary contributor in both cases at 60-77% of total emissions. Next several electricity-based cooling processes (#18 cold storage, #14 drawing/washing/cooling, and #11 pasteurization cooling) were found to each emit in the range of 40-100 g $CO_2$e / kg of final product. Furthermore, steam usage in unit operation #20 from CIP and space heating is potentially significant at approximately 10% of total emissions.

Fluid milk and cream production had emissions of 139 and 129 g $CO_2$e/kg of product, respectively. Like with cottage cheese and whey, but smaller in magnitude, the largest emitters were natural gas based systems, primarily #11 pasteurization heating and #20 CIP and space heat (i.e., boiler-fuel-other), in the order of 20-40 g $CO_2$e/kg of product. Electrical systems with the highest emissions were #9 packaging, #6 cooling, and #3 separator, with emissions from 8-24 g $CO_2$e/kg of product.

**Reducing GHG Emissions.** Opportunities to reduce emissions could come from many of the natural gas and electricity unit operations. As with most energy and GHG reduction strategies, the largest energy consuming equipment or processes have the largest potential impact and should be carefully studied. For the multi-product process flows described in this study (i.e., cottage cheese, whey, fluid milk, and cream production) reduction opportunities should first focus on improvements that consume steam. In particular the steam heated cooker (#13) was found to be the single greatest emitter. Emission reductions would stem from two sources: the cooker and the boiler/steam delivery system. First, reducing steam usage in the cooker could be achieved through improved heat transfer to the curd/whey, reduced heat loss from the process, and developing methods/systems that reduce cooking time or temperature. Secondly, reducing natural gas consumption of a boiler can often be achieved by maintaining proper air/fuel ratio, installing modern design burner, removing scale from heat transfer surfaces, maintaining proper make-up water treatment, repairing failed steam traps, insulating bare steam lines, recovering waste heat from high-temperature exhaust gases or from boiler blowdown, and recovering steam condensate. Similarly, boiler and steam system improvements would translate to emission reductions related to all other unit operations that consume steam, in particular the pasteurization, CIP, and space heating. Pasteurization heat exchangers should maintain high regeneration efficiencies over 90%. Related, current research is ongoing on alternative milk processing technologies that

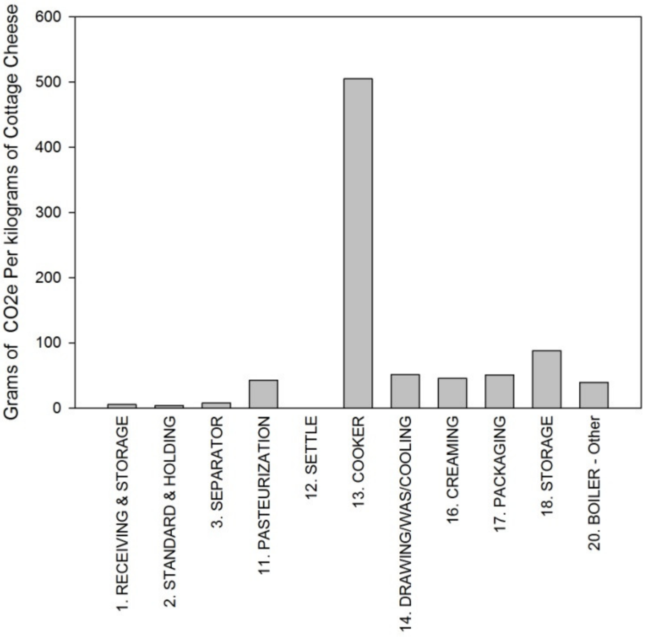

Figure 3. Grams of $CO_2$e Per kilograms of Cottage Cheese Produced. Total emissions of 839.5 g $CO_2$/kg of Cottage Cheese.

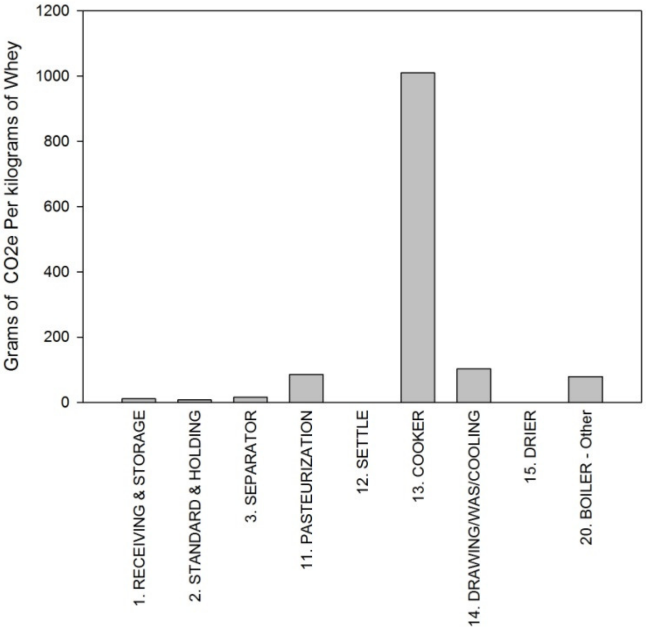

Figure 4. Grams of $CO_2$e Per kilograms of Whey Produced. Total emissions of 1310.6 g $CO_2$/kg of Whey.

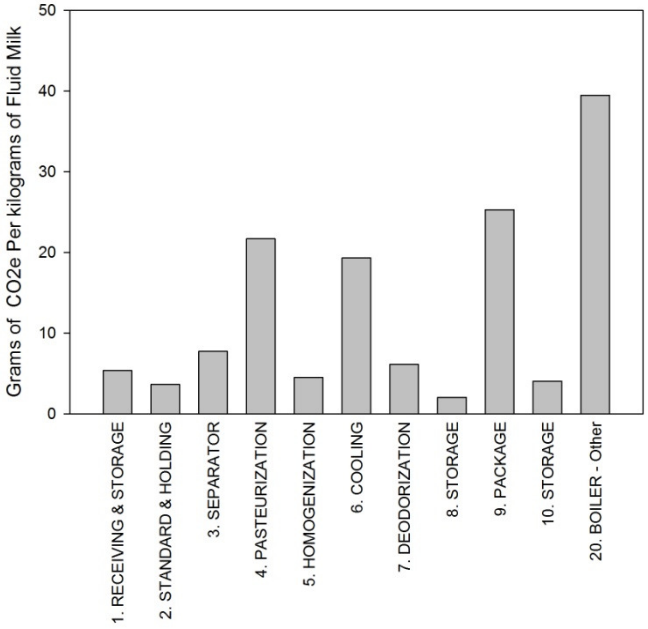

Figure 5. Grams of $CO_2e$ Per kilograms of Fluid milk Produced. Total emissions of 139.2 g $CO_2$/kg of Fluid Milk.

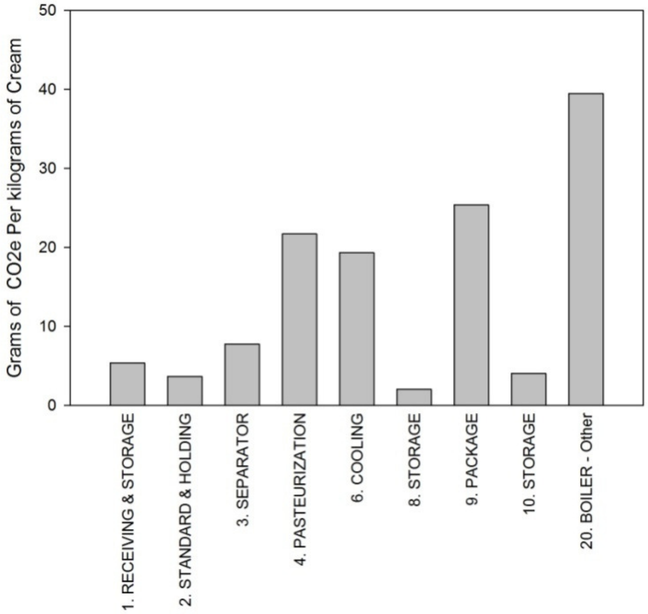

Figure 6. Grams of $CO_2e$ Per kilograms of Cream Produced. Total emissions of 128.7 g $CO_2$/kg of Cream.

Table 2. GHG emissions for each unit operation and product (in grams CO2e per kilogram of final product).

| | **Product Emissions (g $CO_2$e per kg of Final Product)** | | | |
|---|---|---|---|---|
| | **Cottage Cheese** | **Whey** | **Fluid Milk** | **Cream** |
| 1. Receiving & Storage | 5.4 | 10.7 | 5.4 | 5.4 |
| 2. Standard & Holding | 3.6 | 7.3 | 3.6 | 3.6 |
| 3. Separator | 7.7 | 15.5 | 7.7 | 7.7 |
| 4. Pasteurization | | | 21.7 | 21.7 |
| 5. Homogenization | | | 4.5 | |
| 6. Cooling | | | 19.3 | 19.3 |
| 7. Deodorization | | | 6.1 | |
| 8. Cold Storage | | | 2.0 | 2.0 |
| 9. Packaging | | | 25.3 | 25.4 |
| 10. Storage | | | 4.0 | 4.0 |
| 11. Pasteurization | 42.8 | 85.5 | | |
| 12. Settling | 0.0 | 0.0 | | |
| 13. Cooker | 504.8 | 1009.6 | | |
| 14. Drawing/Washing/Cooling | 51.1 | 102.3 | | |
| 15. Dryer | | 0.8 | | |
| 16. Creaming | 45.7 | | | |
| 17. Packaging | 50.8 | | | |
| 18. Storage | 88.1 | | | |
| 19. Refrigeration | | | | |
| 20. Boiler-Other | 39.5 | 78.9 | 39.5 | 39.5 |
| **Total** | 839.5 | 1310.6 | 139.2 | 128.7 |

could significantly reduce energy usage [8]. In addition, lengthening required times between CIP cleanings or low-temperature methods of clean-in-place could significantly reduce natural gas GHG emissions.

Due to the high content of lactic acid in the whey, a high flow of air and the resultant energy loss, is needed to ensure the dried whey product will not be hydroscopic. Caking of the whey in the bag over a relatively short period of time is of high concern. This means that the dryer system must also be large enough that fluid bed dryers are not needed and this also adds to the energy demands and capital expense of the system.

Energy efficiency measures for the electrical systems in dairy processing plants have the potential to reduce GHG emissions. To reduce electricity consumption (i.e., kWh), equipment must either operate at a lower power level or they must operate less time. Electric motors drive many of the unit operations' systems mentioned above, such as packaging lines, refrigeration systems, separators, homogenizers, and more.  So, the use of variable speed drives, properly sized motors, and premium efficient motors can minimize electrical power requirements. Reducing unnecessary operating time can generally be achieved through three methods – the use of computerized energy management systems, individualized timers or controls, or establishing practices and procedures to manually shut off equipment when it is not in use.

## 3.6 SUMMARY AND CONCLUSIONS

Of the four dairy products analyzed, cottage cheese and whey powder were found to require the highest energy input and had GHG emissions of 840 and 1,311 g $CO_2$e/kg of final product, respectively; followed by fluid milk and cream at 139 and 129 g $CO_2$e/kg of final product, respectively. The largest GHG emitting unit operations were cooking, cold storage, drawing/washing/cooling, and pasteurization-cooling. In addition, combined emissions from space heating and CIP were found to be significant, consuming close to the same percentage of NG as all process heating.

Considering that the US processes over $85x10^9$ kg of raw milk each year, the scale is large enough that efforts to reduce energy use have the potential to significantly reduce operating costs and GHG emissions. This paper has identified the unit operations with the greatest potential for significant reductions.

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# 4. SUMMARY AND CONCLUSIONS

The energy consumption and GHG emissions behavior from commercial building's HVAC equipment and dairy processing were studied in this thesis. In commercial buildings, GHG emissions from the operation of HVAC equipment were significantly larger than M&P. It was found that M&P contributes less than 5% of the total GHG emissions during the equipment lifetime. Although electricity and NG consumption generates GHG emissions, GHG emission from electricity use is higher than NG due to smaller source emissions factor of NG. Electricity's source emissions factors play an important role in actual GHG emissions. In dairy processing, whey and cottage cheese production have the largest emissions per unit mass of final product. Based on significant usage, NG based unit operations in dairy processing were the largest GHG emitters. The study also showed that across the entire plant, non-process heating consumes essentially the same amount of NG as process heating. For electricity based unit operations: the separation, cooling and packaging operations were found to be large GHG emitter.

Overall, several high-level conclusions can be drawn from the combined work described in this thesis.

1. This study reaffirms that not all fossil fuel based energy use results in the same GHG emission impact; therefore, component-level studies for building and industrial systems are valuable for better targeting energy efficiency measures to reduce GHG emissions.
2. The source emission factors of electric power generation can vary greatly. The overall magnitude of energy inefficiencies and GHG emissions at power generation origin are

magnified after electricity is distributed to the electric power consumer. GHG emission at the power generation source must be reduced to achieve overall GHG emissions reduction goals.

3. The results of this study were found to be consistent with others – showing that operational energy consumption during equipment’s useful lifespan contributes the overwhelming majority of GHG emissions. Therefore, energy efficiency has a critical impact in reducing both lifetime energy consumption and GHG emissions.