Charting the Course for Sustainability at Aurora Organic Dairy

Phase I: Energy & Greenhouse Gas Life Cycle Assessment

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Abstract

Organic agriculture has sustained consistent growth in the U.S. over the past decade, but very little systemic environmental impact benchmarking has been performed. This study is the first life cycle assessment (LCA) of a large-scale, vertically integrated organic dairy in the U.S. The focus of this study was Aurora Organic Dairy (AOD), a leading provider of private label organic milk in the US. Over the time frame of analysis, April 2007 to March 2008, AOD owned or leased six dairy farms, located in Colorado and Texas, as well as a milk processing plant, located in Colorado. Primary data from AOD farms and processing facilities were used to build a LCA model for benchmarking the greenhouse gas (GHG) emissions and energy consumption across the entire milk production system, from organic feed production to transport of packaged milk to product end of life disposal. Overall GHG emissions were 7.98 kg CO_2e per gallon of packaged liquid milk purchased at the retail location. The major GHG contributors include enteric fermentation (25% of total) and feed production (17% of total). The energy consumption for the entire system was 72.6 MJ (1.65 gallons of gasoline equivalent LHV) per gallon of packaged liquid milk. Potential strategies for reducing the system GHG emissions are discussed including wind energy, animal husbandry techniques, biodiesel, photovoltaic energy, and anaerobic digestion.

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Executive Summary

Objective

The objective of this study was to conduct a life cycle assessment (LCA) of greenhouse gas (GHG) emissions and primary energy consumption for a gallon of Aurora Organic Dairy (AOD) milk from feed to landfill. These life cycle profiles will be used to highlight processes that contribute the greatest GHG and energy impacts across the overall system. This study represents the first LCA for a large-scale vertically integrated dairy operation in the US. The aim of this study is to provide AOD and the broader dairy industry with a tool to benchmark company energy consumption and GHG emissions, as well as identify and evaluate possible company improvement strategies for GHG and energy reduction.

Methods

The milk production system was organized into five stages: the feed production stage, farm operations stage, milk processing stage, distribution stage, and consumer and end of life stage (Figure ES-1). Over the time frame of the analysis, April 2007 to March 2008, AOD operated six dairy farms as well as a milk processing plant. All processes in these stages were modeled using monthly data, to account for the dynamic nature of AOD's operations, and aggregated for annual emissions.

The feed production stage includes the growth, transportation, and processing of all organic feed for the AOD herd. The primary feed types consumed by the AOD dairy cattle were organic forages (pasture grasses and alfalfa hay) and organic grain pre-mix. The growth of the alfalfa hay and grain pre-mix were analyzed using existing LCA datasets. All purchased feed quantities were taken from AOD's monthly records.

The farm operations stage examines all material and energy inputs into farm processes and infrastructure. In addition, on-farm diffuse emissions from raising AOD dairy cattle, such as emissions from enteric fermentation and manure management, were included in the farm operations stage. Materials used at each farm were taken from AOD's purchasing lists, while energy usage was taken from monthly utility bills. GHG emissions from enteric fermentation and manure management were modeled on a monthly basis according to 2006 International Panel on Climate Change (IPCC) National Greenhouse Gas Inventory Guidelines. Energy consumption and GHG emissions from live animals leaving the milk production system (bull calves and culled cows) were allocated away from the fluid milk life cycle inventory. Energy and GHG emissions from raw milk at the farm gate were also analyzed based on energy corrected milk (ECM) in order to draw comparisons to existing studies. ECM is a common correction factor for dairy products which considers the fat and protein content of the raw milk.

The milk processing stage includes the energy and GHG emissions associated with the transport of raw milk to AOD's processing facility, the processing of raw milk into salable product, and the manufacturing of packaging materials. Transportation was examined using AOD's monthly shipment records. Processing and packaging energy were taken from AOD milk plant utility bills. Packaging material weights were provided by AOD employees and company records.

The distribution stage includes the energy and emissions associated with the transportation of AOD product to a cold storage facility, the storing of AOD product, and the transportation of AOD product to retail distribution centers. All transportation distances were modeled using AOD's records. Energy and emissions from cold storage were modeled by determining both the floor space of the facility required for AOD product and the associated electricity required to refrigerate that portion of the facility.

The consumer and end-of-life stage was modeled based on literature values and national averages. Processes accounted for in the consumer and end-of-life stage include distribution center refrigeration, distribution center to retail refrigerated transport, retail refrigeration, consumer transport and at-home refrigeration, waste management transport and landfill gas emissions.

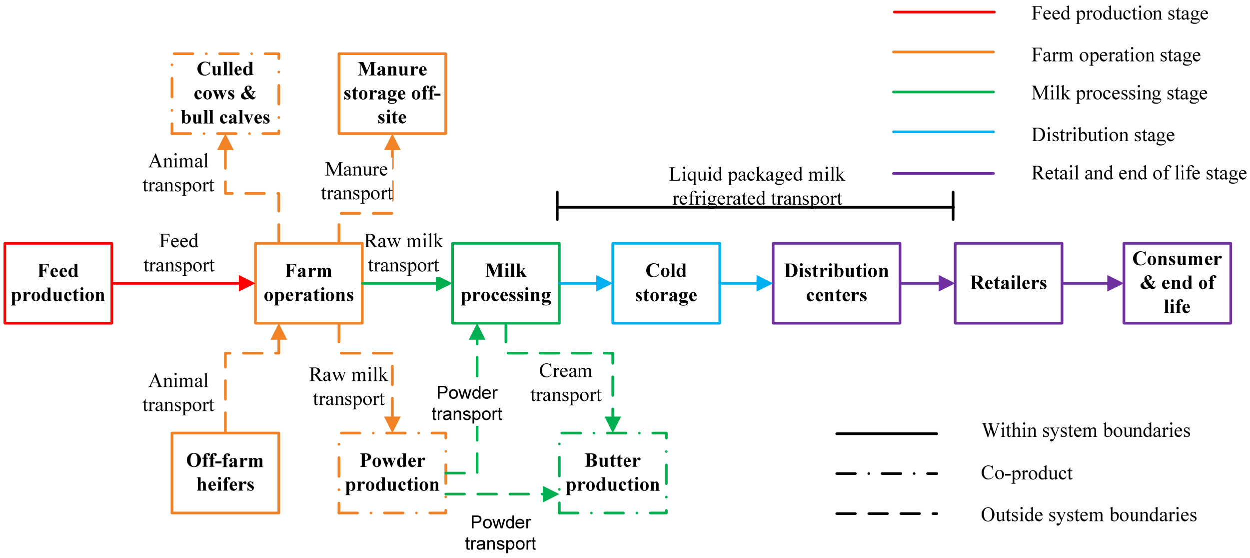

Figure ES- 1: AOD dairy flow diagram for entire milk system

Results

Overall life cycle GHG emissions were 7.98 kg CO_2e and 72.60 MJ (1.65 gallons of gasoline equivalent LHV) per gallon of final packaged liquid milk. The major GHG contributors include enteric fermentation (25% of total) and feed production (17% of total) (Figure ES-1). The primary energy contributors include feed production (14% of total) and product storage and transport (15% of total) (Figure ES-2).

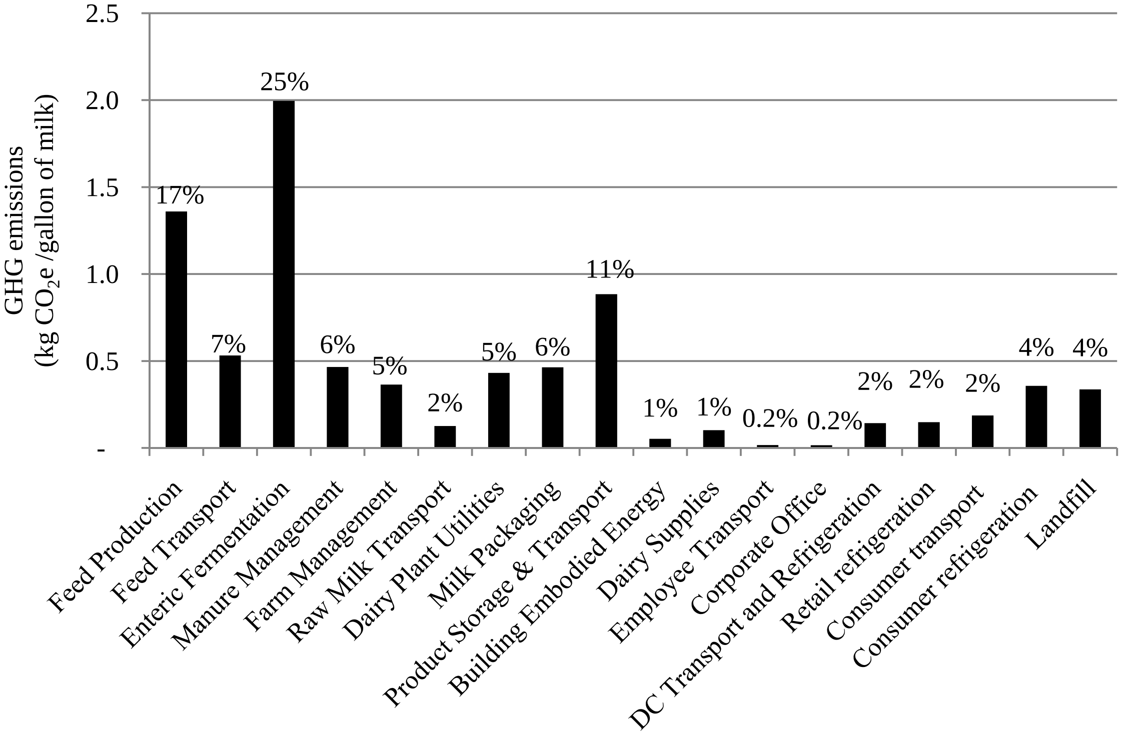

Figure ES- 2: Distribution of life cycle GHG emissions for one gallon of packaged liquid milk

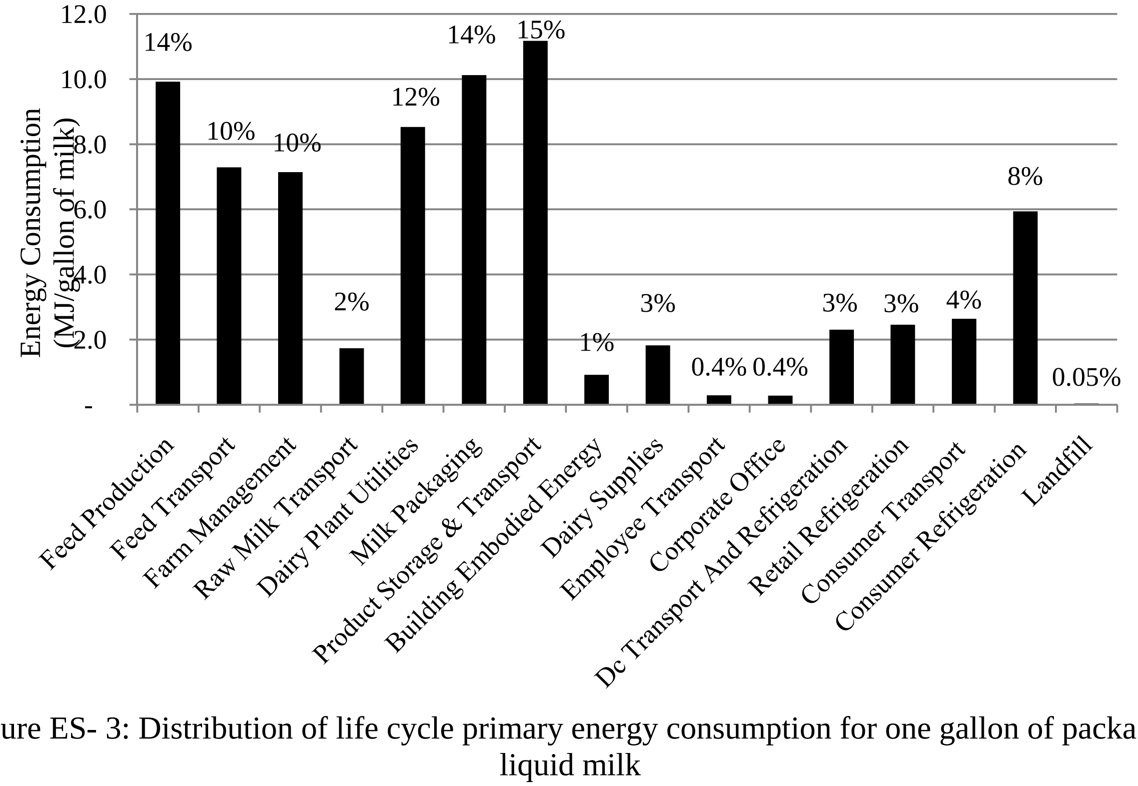

Figure ES- 3: Distribution of life cycle primary energy consumption for one gallon of packaged liquid milk

For raw milk at the farm gate, 1.35 kg CO_2e were emitted per kg ECM. GHG emissions per kg ECM varied between the six AOD farms; the Dipple farm had the highest emissions per ECM and the High Plains farm had the lowest emissions per ECM. The relatively high GHG value associated with Coldwater is likely due to production inefficiency related to scaling up of operations over the time frame of analysis. Coldwater started operation in July 2007; refer to Figure 35, for a perspective on the ramp-up of the Coldwater Farm and associated reduction in GHG emissions. The high GHG value associated with the Dipple farm is likely due to the large manure management emissions (Figure ES-3). These high manure management emissions are due to high methane emissions associated with employing a more liquid-based manure management practice, as compared to other AOD farms. Additionally, manure solids separation problems due to the combination of liquid flushing and sand bedding further increased GHG emissions at Dipple. However, it is important to note that this model represents a snapshot in time between April 2007 through March 2008, and may not reflect current situations or efficiencies at each farm.

Table ES- 1: GHG emissions per ECM for the six AOD farms and entire company, both at farm gate and including raw milk transport

	kg CO_2e/kg ECM with raw milk transport	kg CO_2e/kg ECM at farm gate
High Plains	1.10	1.10
Platteville	1.23	1.23
Ray-Glo	1.13	1.12
Dipple	1.96	1.88
Dublin	1.55	1.48
Coldwater	1.46	1.41
Overall	1.38	1.35

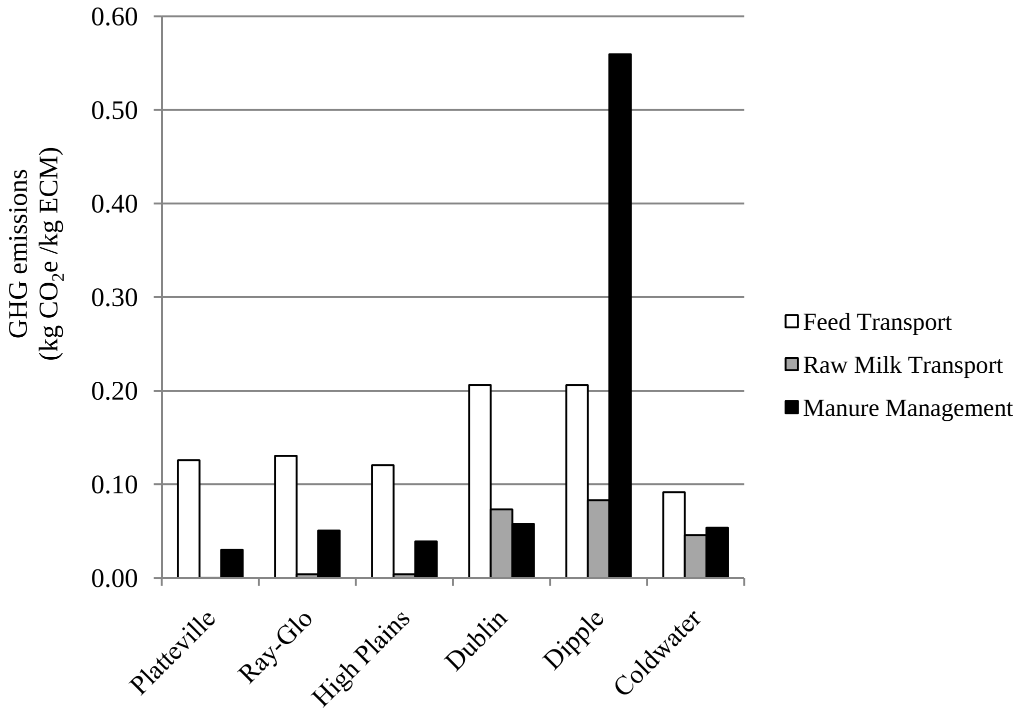

Figure ES- 4: Comparison of raw milk transport, feed transport, and manure management for the six AOD farms based on the kg ECM produced at each farm

Recommendations for improvement

Several key recommendations that may help AOD improve the GHG and energy performance of its operations were identified in this study. These recommendations are as follows:

- Improve the manure management system at the Dipple Farm. It is recommended that AOD either transition to a dry manure management system or flare the methane from the lagoons to reduce emissions at Dipple.
- Examine ways in which diffuse emissions from enteric fermentation can be abated. It is recommended that AOD build partnerships with animal scientists at Colorado State University, working together to devise methods for mitigating enteric fermentation through the manipulation of animal diet or other practices.
- Research means to utilize alternative energy at AOD facilities. Significant potential exists, on AOD farms, for the employment of alternative energy technologies, which can displace energy created from non-renewable sources.
- Perform energy audits and make energy efficiency improvements at older AOD facilities.

- Continue to track company energy consumption and GHG emissions on an annual basis.

Limitations and future work

The main limitation of this study was the lack of available datasets for organic crop production in the U.S. This study, therefore, relied on LCA datasets from organic crop production in Switzerland and conventional crop production in the US. Geographic coverage and farming technique, as it is currently represented in the model, is not precise to this study. Additionally, caution must be exercised in comparing life cycle results from this study with other results published in the literature. Differences in methods and model parameters can influence the comparison and lead to inaccurate conclusions. This study is intended to be used as a benchmark for the timeframe the study was conducted (April 2007-March 2008), and should not be used to assess GHG emissions or energy consumption from the milk life cycle for any other timeframe.

This is the first phase of a two phase study through University of Michigan funded by the AOD Foundation. The second phase looks at additional sustainability indicators, including social and economic indicators. Together, these two studies will provide AOD and other dairies with a comprehensive framework that can be used to improve the sustainability of its operations.

1. Introduction

1.1. Purpose

The objective of this study was to conduct a life cycle assessment (LCA) for a large-scale, vertically integrated organic dairy in the US. Specifically, this study examines the primary energy consumption and greenhouse gas (GHG) emissions of milk production at the dairy company Aurora Organic Dairy (AOD).

1.2. AOD & industry background

AOD is a leading U.S. provider of private-label organic milk and butter. AOD owns six dairy farms, collectively milking approximately 14,000 cows, as well as a processing facility, which has the capacity to process up to 37 million gallons of milk annually. All farms and the processing facility are owned or leased and operated by AOD, making them one of the largest vertically integrated organic dairies in the country.

The market for organic dairy products is growing quickly. During the 1990s, organic dairy was the most rapidly growing segment of the organic food industry, with a growth of over 500% between 1994 and 1999 (Wellson, 2007). In response to this consumer demand, the United States Department of Agriculture (USDA) developed national organic standards for many foods in October 2002 in compliance with the Organic Foods Production Act of 1990 (OFPA). The national organic standards ensure that all practices, methods, and substances used on a certified organic farm adhere to OFPA. At the same time, each organic farm varies in specific practices and philosophies in implementing the provisions of OFPA, which are set forth in an Organic System Plan (OSP), which is reviewed, refined and overseen by an independent accredited certifying agent approved and certified by the USDA. The national organic standards, as they apply to dairy operations and are incorporated into a dairy producer's OSP, include specifications of required farm practices. For instance, organic farming excludes the use of synthetic fertilizers and pesticides, plant growth regulators, and genetically modified organisms. Land requirements, soil fertility and crop management, origin of livestock, livestock feed, livestock health, and livestock living conditions all must be implemented in accordance with the national organic standards and are required to be incorporated into the dairy producer's OSP. Further, conventional-to-organic transition requirements are also included in the national organic standards. Specifically, land requirements mandate that field or cropland must have had no prohibited substances applied to it for a period of three years immediately preceding harvest of the crop (USDA, 2000). Dairy cows must be under continuous organic management, without receiving antibiotics or synthetic growth hormones, beginning no later than one year prior to the production of the milk or milk products. All dairy cattle must consume only organic feed. The USDA has strict labeling regulations to provide information to consumers, and processed foods with the USDA organic logo must contain at least 95% organic ingredients (USDA, 2000).

In 2005, sales of organic milk and cream were just over $1 billion, a 25% increase from 2004. Overall milk sales have remained constant since the mid 1980s, and organic milk now makes up 6% of total retail milk sales (Dimitri & Venezia, 2007). The demand for organic milk grew so quickly that in 2005 and 2006, the media reported shortages of the product (Weinraub & Nicholls, 2005). The majority of the organic milk available for purchase by consumers is supplied from three companies: Organic Valley established in 1988, Horizon Organic established in 1992, and AOD established in 2003. In 2007, 75% of branded organic milk was supplied by Organic Valley and Horizon Organic, while most of the private-label organic milk was provided by Aurora Organic Dairy (Dimitri & Venezia, 2007).

1.3. Environmental importance of dairy systems

In a report titled 'Livestock's Long Shadow: Environmental Issues and Options,' the Food and Agriculture Organization of the United Nations (Steinfeld H. , Gerber, Wassenaar, Castel, Rosales, & de Haan, 2006) determined that the livestock sector was "one of the top two or three most significant contributors to the most serious environmental problems, at every scale from local to global." One of these very serious environmental problems is global climate change due to GHG emissions. According to the IPCC 4th Assessment Report (IPCC, 2007), global surface temperature is expected to rise 1.1°C to 6.4°C by the year 2100, which could have devastating effects on natural and social systems. The three main GHGs of the dairy system are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). According to the "Livestock's Long Shadow" report (2006), the livestock sector is responsible for 18% of global GHG emissions, which is a higher percentage than global transportation. The livestock sector accounts for 37% of global anthropogenic CH_4 emissions and 65% of global anthropogenic N_2O emissions. According to the USDA's 1990-2005 US Agriculture and Forestry GHG Inventory, livestock contribute approximately 3.5% of total U.S. GHG emissions. Dairy cattle were the second largest source of these GHG emissions, behind cattle production for beef (USDA, 2008).

The largest portion of GHG emissions from the livestock sector results from on farm diffuse emissions due to enteric fermentation and manure management. Enteric fermentation is the process of bacteria in the animal's stomach (rumen) breaking down carbohydrates in the animal feed. The rumen supports this microbial fermentation, which allows ruminants the ability to digest cellulose. CH_4 is released as a by-product of this digestion. CH_4 is also released when manure decomposes anaerobically. Liquid management systems and high temperatures lead to more anaerobic decomposition, while solid management and cooler temperatures lead to more aerobic decomposition. Another important portion of GHG emissions from the livestock sector is N_2O emissions from manure and soil management. These N_2O emissions occur in three forms: direct, indirect, and runoff. Direct N_2O emissions occur through the processes of nitrification, followed by denitrification, of the nitrogen in the manure. Nitrification of ammonia to nitrate occurs aerobically, followed by the anaerobic denitrification of nitrate into N_2O and N_2. Emissions depend on the nitrogen content of manure, the type of management system and the duration of that management system. Indirect N_2O emissions result from simple organic forms of nitrogen (i.e. urea) oxidizing to create ammonia, which easily diffuses into the surrounding air, a portion of which react to form N_2O emissions. Nitrogen losses due to runoff and leaching will also lead to N_2O emissions in a similar manner (IPCC, 2006). Livestock contributions to the nitrogen cycle can be seen below in Figure 1.

The importance of studying the livestock industry and the dairy industry in particular cannot be overlooked. With the substantial environmental impact of the livestock sector and dairy cattle being the second largest source of livestock GHG emissions, it is vital to study and implement environmental abatement solutions for the dairy industry.

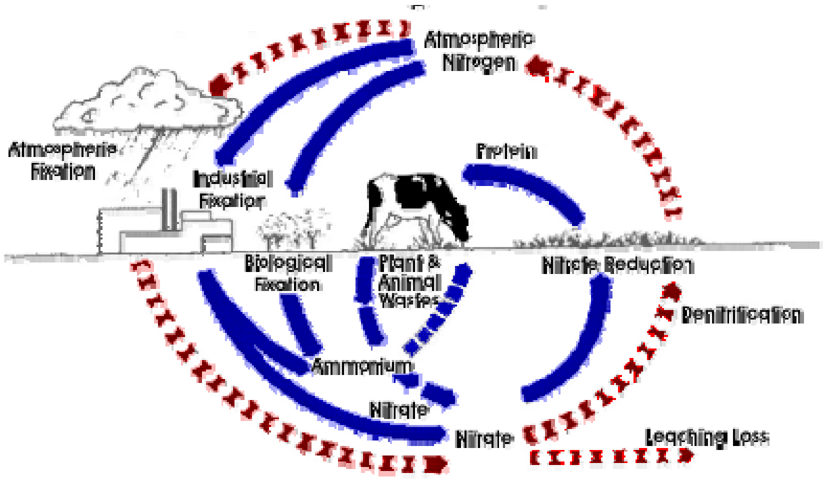

Figure 1: Dairy influence to the nitrogen cycle (EPA)

1.4. Introduction to the life cycle assessment (ISO, 1997)

LCA is a systematic approach to determine the environmental burdens of a product, in this case a gallon of milk. The International Standard Organization (ISO) has defined the principles and framework for carrying out and reporting LCA studies. LCA has four main components in its framework: goal and scope definition, inventory analysis, impact assessment, and interpretation (Figure 2). LCA typically does not address the economic or social characteristics of a product.

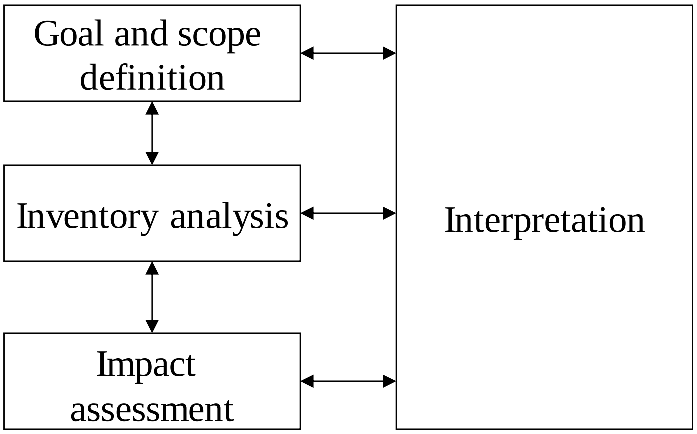

Figure 2: Phases of a LCA (ISO, 1997)

1.4.1. *Goal and scope definition*

The goal and scope phase of the LCA framework defines and describes the product, establishes the context in which the assessment is made, and identifies the system boundary and the time frame of the study. In addition, the goal of a LCA should clearly state the intended application and reasons for conducting the study. LCA is an iterative technique; consequently the scope of the assessment may need to be altered while the study is being conducted.

The scope of a LCA should include the following parts:

- the functions of the product system
- the functional unit
- the product system to be studied
- the product system boundaries
- allocation procedures
- types of impact and methodology of impact assessment
- data requirements, assumptions, and limitations

The above aspects of a LCA in terms of this study are discussed in Section 3 Methodology.

1.4.2. Function and functional unit

The scope of the LCA, as stated above, should define the functions of the system being studied. A functional unit is the measure of the performance of the functional outputs of the product system. The primary purpose of a functional unit is to provide a reference to which the inputs and outputs are related. A system may have a number of possible functions and the one chosen is dependent on the goals and scope of the study. The functional unit considered in this study was one gallon of packaged liquid milk.

1.4.3. System boundaries

The system boundaries determine which processes are included in the LCA study. Factors that determine the system boundaries include the intended application and audience, the assumptions made, the cut-off criteria, and the data constraints. The selection of inputs and outputs, the level of aggregation within a data category, and the modeling of the system should be consistent with the goal of the study. The system boundaries for this study are discussed in Section 2.1 Goal and Scope.

1.4.4. Data quality requirements

Data quality requirements specify the general characteristics of the data needed for the study. Data quality requirements should address:

- time-related coverage
- geographical coverage
- technology coverage
- precision
- completeness
- representativeness of the data
- consistency and reproducibility of the methods used throughout the LCA
- sources of the data and their representativeness uncertainty of the information

Data quality limitations, specifically relating to geographic coverage, are examined in Section 5 Discussion.

1.4.5. Life cycle inventory analysis

The inventory analysis involves compiling an inventory of the relevant inputs and outputs of a product system. These inputs and outputs could include the use of resources and releases to air, water, and land associated with the product system. Energy, material, GHG, and all other inputs and outputs were inventoried for this study, with exact inventory methods discussed in Section 3 Methodology, detailed inventory results can be found in Appendix A – Detailed Results.

1.4.6. Data collection and calculation procedures

The procedures used for data collection may vary depending on the scope and intended application of the study. Data collection can be a resource-intensive process, and practical constraints should be considered in the scope and documented in the report. Specifically, significant calculation considerations include allocation procedures. Allocation procedures are needed when dealing with systems involving multiple products. Allocations involved in this study include third party cream, powder, butter, bull calves, and culled cows. Allocation procedures for these co-products are discussed in Section 3.7 Allocation methods.

1.4.7. Impact assessment

The impact assessment considers the potential human and environmental effects associated with the inputs and outputs collected and calculated in the inventory analysis. ISO recognizes that impact assessment is still in the early stages of development. The level of detail, choice of impacts evaluated, and methodologies used are tied to the goal and scope of the study. The impact assessment phase may include elements such as assigning inventory data to impact categories (classification), modeling the inventory data within impact categories (characterization), and aggregating the results in very specific cases and only when meaningful (weighting). Note that there are no generally accepted methodologies for consistently and accurately categorizing inventory data to determine specific potential environmental impacts. However, the approach for categorization of GHG emissions using global warming potential, which was employed in this study, is the most widely used methodology for impact assessment.

1.4.8. Interpretation

Interpretation evaluates impact assessment and inventory analysis with respect to the objectives of the study. The results of this interpretation may be presented in the report in the form of conclusions and recommendations to decision-makers. The interpretation should also reflect the results of any sensitivity analysis that is performed in the study.

1.4.9. Limitations and benefits of LCA

Choices and assumptions made in the LCA model may be subjective. Results of LCA studies for global and regional issues may not be appropriate for local applications, and local studies may not be appropriate for assessing global or regional issues. The accuracy of LCA studies may be dependent on the accessibility and availability of relevant data. Specifically, spatial and temporal dimensions of data may be limited due to availability and accessibility of good quality data. This study only considers energy consumption and GHG emissions, which are not the only factors in evaluating environmental performance. Full environmental performance evaluation might consider other factors such as land use, water use, solid waste, heavy metals, and toxins.

LCAs can identify processes in a product's development that have disproportionate negative environmental impacts or *hot spots*. Identifying these processes in the life cycle will narrow the focus when later improving the product's environmental impact. LCA studies can assist decision-making for a variety of sectors including industry, government, and non-governmental organizations. Further, LCAs can potentially assist in product marketing at the retail level. Overall, the information developed in the LCA should be used as part of a much more comprehensive decision-making process or to understand the broad trade-offs of a product system.

1.5. Review of previous milk LCAs

LCA methodology has been used to compare the environmental performance of conventional and organic milk production in Sweden (Cederberg & Mattsson, 2000), Germany (Haas, Wetterrich, & Köpke, 2001), Finland (Grönroos, Seppala, Voutilainen, Seuri, & Koikkalainen, 2006), and the Netherlands (Thomassen, Calker, Smits, Iepema, & de Boer, 2008), and to assess the GHG emissions from milk production in Ireland (Casey & Holden, 2005). The entire milk supply chain (farm production, transport, milk processing, and packaging) in Spain (Hospido, Moreira, & Feijoo, 2003) and Sweden (Sonesson & Berlin, 2003) has also been analyzed with LCA methods. All past dairy studies have been conducted on relatively small farms, and no past studies have looked at the full life cycle of milk in the U.S. This effort represents the first comprehensive LCA of large-scale milk production in the U.S., as well as the first LCA of a vertically integrated organic dairy.

1.6. Objectives

The primary objectives of this research were the following:

- To model the GHG and energy life cycle of a unit of AOD milk from feed to landfill;
- To highlight processes which contribute the greatest energy and GHG impacts across the overall system;
- To use the total energy consumption and GHG emissions as a benchmark for improvement; and
- To identify and evaluate possible strategies for GHG and energy reduction within AOD's organic dairy system.

2. *System Description*

2.1. *Goal and scope*

This study considered the milk life cycle over one-year, from April 2007 until March 2008. Averaging the GHG emissions and energy consumption over this time period should account for any seasonal changes amplified by the prevalence of natural systems inherent in dairy operations. Figure 3 shows the entire milk life cycle including all co-products that are considered outside the scope of this LCA.

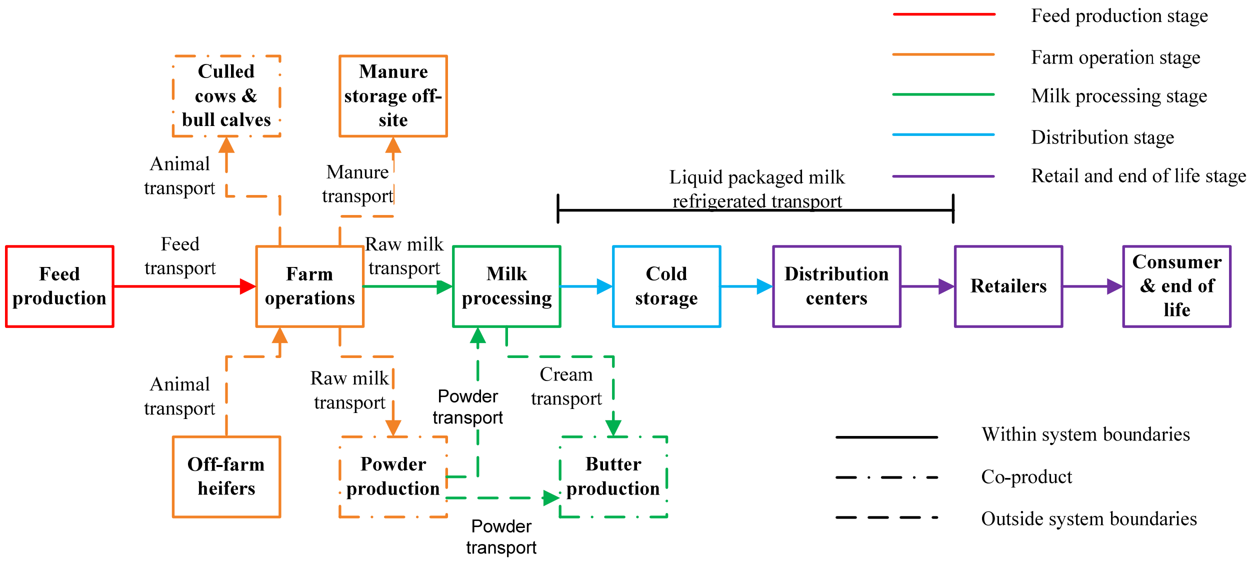

Figure 3: AOD dairy flow diagram for entire milk system

For the purposes of this study, the process flow of one gallon of AOD milk starts with the production of the cattle feed. The herd grazes on organic pasture grown by AOD and organic-certified partner farms during the growing season; however, the feed production stage only considers purchased feed. The farm operations stage includes the production of organic pasture. The feed is transported to one of AOD's farms where it is consumed by the herd. The milking herd produces milk, which is transported to AOD's milk processing plant where it is pasteurized, homogenized, and packaged into the final product. Next, the packaged liquid milk is transported via refrigerated trucks to a cold storage facility, and continues on to the distribution centers of AOD's customers. At this point the product ceases to be under AOD's control. After storage at the distribution centers, the milk is transported to retail centers across the country and finally bought by US consumers who consume the milk and dispose of the packaging.

In addition to the primary output, one gallon of milk, there are several other outputs from the system. These outputs include co-products, a product coming out of the system that has value, and waste, a product generated in the system without value. The co-products in this system are culled cows, bull calves, milk powder, and butter. When a cow is unable to produce milk, either too old or born as a male, he or she is sold for meat and other products. In both of these cases, the animal is outside the boundaries of this LCA once it leaves the farm. These cows are then replaced by a heifer, the raising of which is included in the boundaries of this LCA. Occasionally, some of the raw milk produced on AOD's farms is transported and to a milk powder processing facility. Some of the powder that is created is shipped to AOD's milk processing plant to be mixed into fortified milk to be sold in California, where state regulations demand higher milk solids content than the industry norm. Any powder that is not added back into a final packaged milk product is not included in this LCA. Finally, cream is separated from the milk and transported to be made into butter, again outside the scope of this LCA. The included processes in the milk life-cycle, excluding energy consumption and GHG emissions associated with the co-products, combines to define the impact of one gallon of organic milk.

2.2. Feed production stage

The cows on any of AOD's farms get a consistent diet according to their lactation cycle. In addition to pasture during the growing season, an AOD dairy cow's diet is consistent with industry averages: 41% organic alfalfa hay, 41% organic grain premix, 17% organic grass hay, and 1% minerals. All the ingredients are blended together at AOD's farms into a proprietary "Total Mixed Ration" (TMR) that ensures each feed portion contains the right proportion of ingredients. The organic grain pre-mix is made up of 50% ground corn, 17% soybean meal, 14% soybean hulls, 14% wheat, and 5% minerals, which is consistent with industry averages.

Market demands, climate, and other circumstances have led to geographically disparate organic feed production. The majority of AOD's feed purchases come mainly from suppliers and brokers throughout the Rocky Mountain and Plains regions. The distances each type of feed travels from the different feed suppliers were used to calculate the environmental impact of the feed transportation in the life cycle analysis. The weighted average distance each feed type travels to AOD's farms was calculated using the percentage of feed provided by each supplier. The weighted average distance for each feed component is in Table 1, the locations of the six AOD farms examined in this study are show in Figure 6.

Table 1: Weighted average distance (in miles) each feed type travels to each of AOD's farms

	AOD Farm					
Organic Feed Type	High Plains	Platteville	Dublin	Dipple	Coldwater	Ray-Glo
Grass Hay	295	200	425	425	490	295
Dry Minerals	1205	1185	70	70	1185	1205
Alfalfa	710	740	1360	1360	725	710
Premix	395	365	655	655	70	395

The majority of all the non-pasture feed consumed by the cows on AOD’s farms is supplied by two organic-certified feed brokers in Idaho and Texas. Both of these consolidators buy feed from many different suppliers and from many different farms. In the case of the grain pre-mix, the consolidator mixes the ingredients to make a blended feed concentrate. The overview of the flow of the feed system is shown in Figure 4.

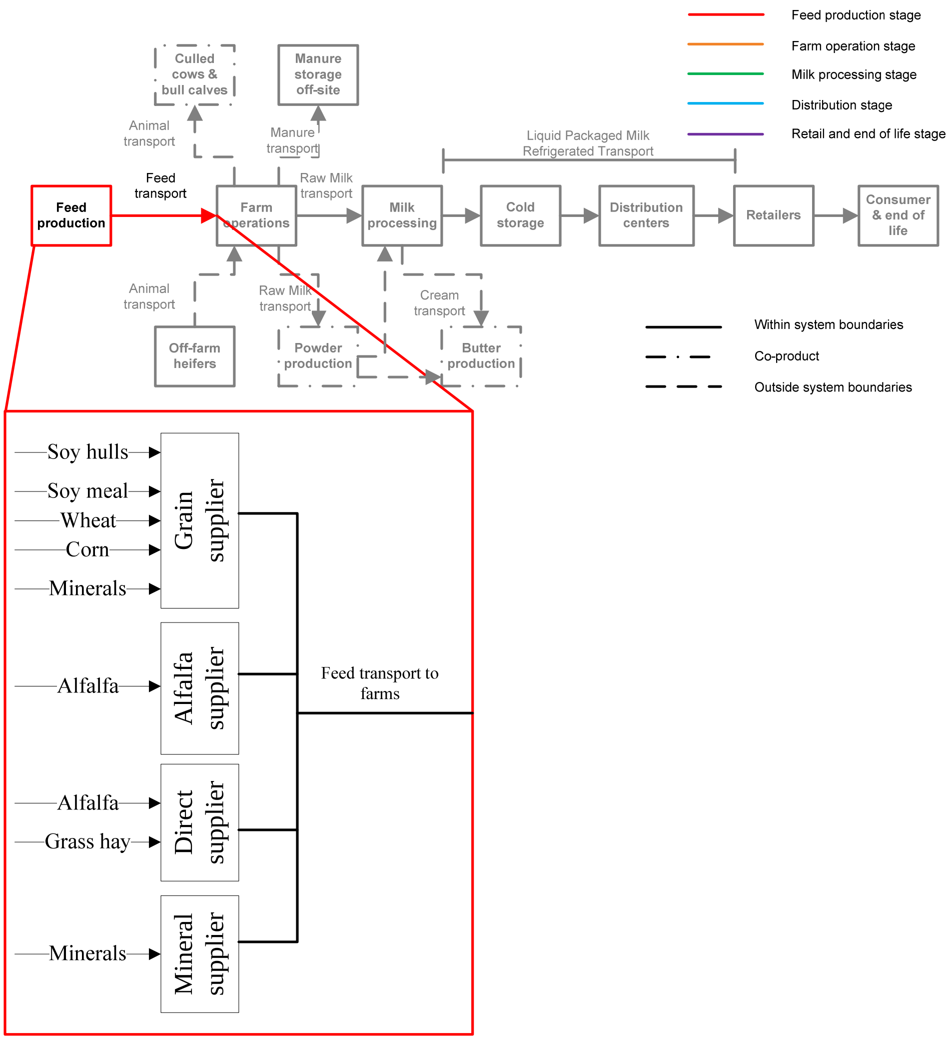

Figure 4: Process flow diagram for feed production stage

2.3. Farm operations stage

This study considers the six AOD farms in operation during the one year time frame (April 2007 – March 2008). Three of the farms studied are located in Colorado and three are located in Texas. Figure 6 shows the location of all six farms taken into account in the LCA. All of the farms transport their milk to a single location for processing. Over the year studied, all six farms collectively milked approximately 14,000 cows on average. The farm system considered in this analysis can be seen in Figure 5. An overview of each farm examined during this study is shown in Table 2.

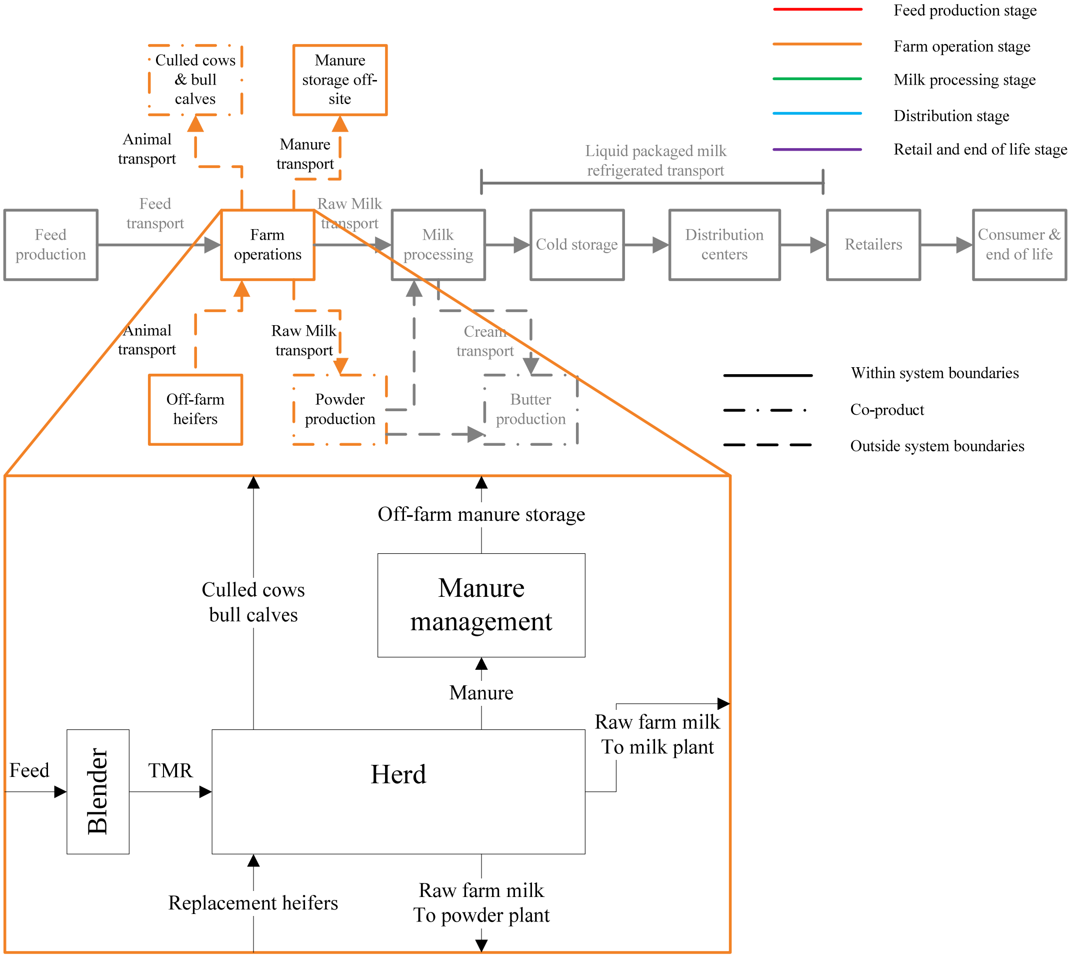

Figure 5: Flow diagram of farm operation stage

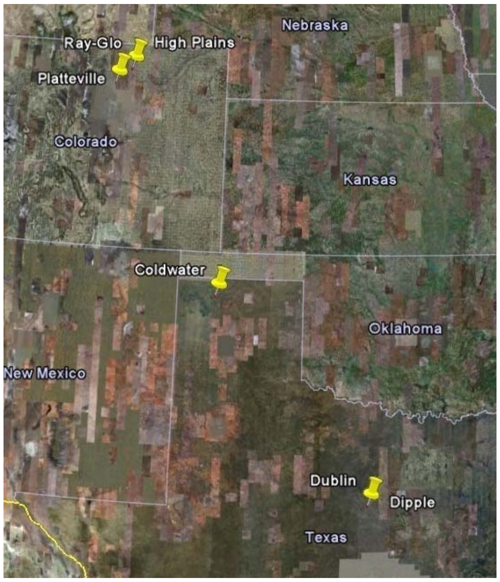

Figure 6: Location of AOD's 6 dairy farms; due to their close proximity Ray-Glo Ray-Glo and High Plains, as well as Dublin and Dipple, are represented by one push pin.

Table 2: Characteristics of the six AOD farms

	Coldwater	Dipple	Dublin	High Plains	Platteville	Ray-Glo
Location	Stratford, Texas	Dublin, Texas	Dublin, Texas	Kersey, Colorado	Platteville, Colorado	Kersey, Colorado
Climate description	Semi-arid	Humid Sub-tropical		Semi-arid	Semi-arid	Semi-arid
Average milking herd size*	5,250	1,780	3,300	3,690	940	630
Pasture area for milking cows*	930 acres	2,800 acres of organic pasture used for either milking or dry cows with a total farm area of 3000 acres		660 acres	270 acres	130 acres
Pasture area for dry cows*	150 acres			450 acres	120 acres	100 acres
Percentage of milk production*	32%	11%	20%	25%	6%	6%
Barn type	West – freestall East – open lot	Freestall	Open lot	Freestall	Open lot	Open lot
Months operating during time frame of study	Jul 2007 – Mar 2008	Apr 2007 – Mar 2008	Apr 2007 – Dec 2007	Apr 2007 – Mar 2008	Apr 2007 – Mar 2008	Apr 2007 – Mar 2008

*This data is based on historical operations and may not reflect the current facilities

AOD is a fast-changing, dynamic company, and their farm operations are no exception. Consequently there were changes to AOD's farms over the time frame examined in this study. Coldwater started producing milk in July of 2007, making it the newest dairy farm in AOD's operation. Over the time frame of this study, Coldwater began operation and scaled up to become the largest of AOD's six farms. In January 2008, AOD stopped milk production at Dublin, leaving Dipple, the smaller of the two farms, as their only farm in Dublin Texas. While both farms were operational they were treated almost as one farm. High Plains is the largest of AOD's Colorado farms containing on average 3,690 milking cows. At this farm, herd size and management practices were fairly stable during the one year period examined by this study. Platteville, AOD's first and oldest farm, is located in Platteville, CO, adjacent to AOD's organic processing plant. Platteville went through changes during the time frame of this study, from a farm with 3,000 milking cows to less than 1,000 milking cows.

AOD utilizes two different styles of animal housing on their farms: freestall barns and open lots. In free stall barns, the cows have access to exercise pens outside of the barn at all times, and they are given bedding inside the barn for comfort.. In open lots the animals are housed in large pens with a roof shelter to help shield them from bad weather. The cows on all farms are also given access to pasture during the growing season on both AOD's and organic-certified neighboring partners' property.

On most of AOD's farms, the manure is managed in a similar way. All milking parlor waste is flushed into a lagoon, and any waste in the stalls is removed via scraping or dry-vacuum. Removed manure is stored for spreading on AOD pasture, spreading on neighboring fields, or sent to composting facilities. In contrast, Dipple utilized a water-based system where the manure was flushed into a lagoon not only from the milking parlor but also from the stalls.

The life stages of a dairy cow determine how a dairy farm must operate and a general understanding of these life stages can lead to a greater understanding of the system under investigation. After the cow's nine month gestation period results in a calf, the cow begins the milking process. The lactating cow is impregnated three months into her lactation period, and continues to produce milk for six months into her pregnancy. The final three months of her pregnancy, the cow is no longer milked in order to provide rest and recovery. These stages repeat and typically result in each cow calving once a year, while producing milk for nine months of that year. This management design increases efficiency in milk production by maximizing the lactation periods. Lactating cows typically yield four calves (or lactation periods) before they are sold, while replacement heifers are either raised from AOD-born or purchased from other farms. Figure 7 shows the life cycle of a typical dairy cow from calf to end of productive life.

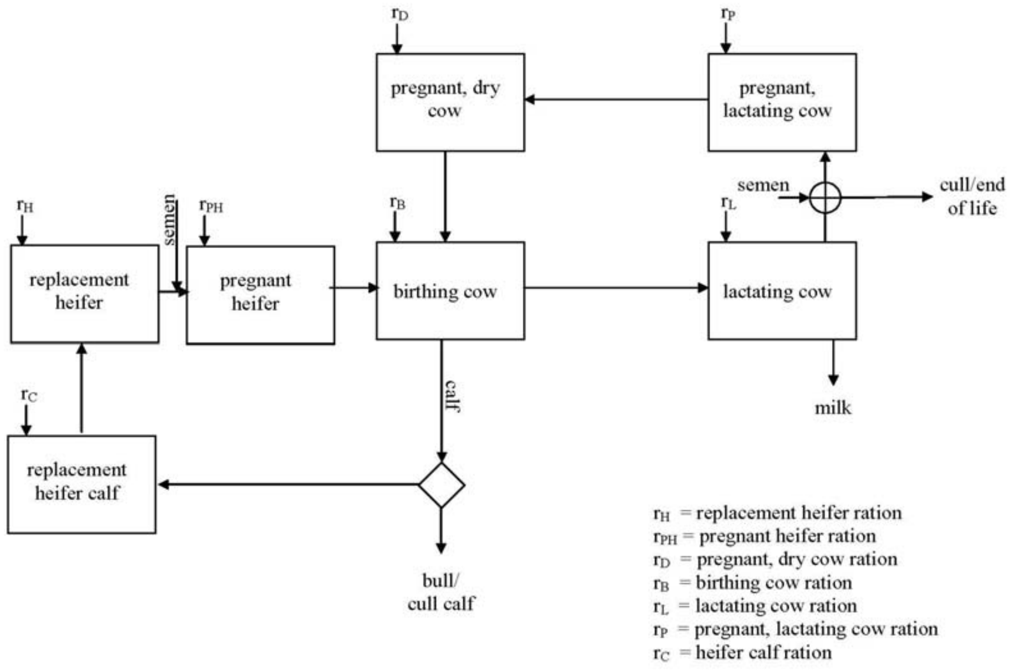

Figure 7: Life cycle of a typical dairy cow

The management of calves on AOD's farms varies by state and has changed in the time since data was gathered for this study. Typically female calves are raised on AOD farms until four months of age. Next, they are raised on organic-certified partner farms until they are ready to calf and are old enough to milk (at approximately two years of age), at which point they are reintegrated into AOD herds. Some calves stay on AOD facilities the entire time prior to calving and milking. The male calves are sold off the farm within 24 hours of their calving and never reintegrated into AOD's system. The female calves born on the farms in Texas, however, were not raised on an AOD farm during this study; both female and male calves were sold within 24 hours of calving. An overview of each farm examined during this study is shown in Table 2.

2.4. Milk processing stage

AOD is a vertically integrated dairy, owning and operating a milk plant in addition to its farms. AOD's milk plant is a state-of-the-art facility and one of the few plants in the U.S. to continuously process organic milk. In the dairy industry, a *continuous process* facility is one in which milk is pasteurized constantly as it flows through the facility, except when production is stopped to clean the equipment. Conversely, most dairy companies have a batch process plant in which a large volume of milk is pasteurized and processed all at one time. Afterwards, the system is cleaned and the next *batch* is processed. AOD's ultra-pasteurization milk plant is located on the same property as their Platteville dairy farm in Central Colorado (Figure 9). The raw milk processed at AOD's milk plant originates from AOD farms where it is chilled and transported in insulated tankers to the processing plant. Raw milk is transferred from tankers to refrigerated stainless steel silos at the milk plant. The milk is never exposed to human contact, or bacteria. All cream is removed from the milk during processing and partially added back into the milk to provide for different fat contents in the final liquid packaged milk product. Excess cream is shipped to a co-packer for butter production (butter production is not included in this LCA). Milk shipped to California has additional milk powder added into the final product to abide by state dairy standards. All milk powder originates from AOD farms and is processed by a co-packer. The entire processing system is managed with strict accordance to USDA national organic standards.

Final liquid milk is packaged in gallon and half–gallon containers. Half-gallon packaging dominates the product line, accounting for 98% per unit of all final liquid milk packaging types. Half-gallons containers are gable top cartons constructed of plastic coated paperboard. Gallon packaging is manufactured at the AOD milk plant using high density polyethylene (HDPE) in a blow molding process. All final liquid packaged milk is boxed in secondary packaging of corrugated cardboard, stacked on wooden pallets, and wrapped in low density polyethylene (LDPE) film for shipping. Milk is packaged and shipped in three ways according to how many units of milk are packaged together: 3 count (3 CT), 4 count (4 CT), and 6 count (6 CT). 3 CT packages consist of three half-gallons and are generally shipped to wholesalers. 4 CT packages consist of the gallon milk with 4 gallons per package, and 6 CT packages consist of six half-gallons and are shipped to most general purpose grocery retailers.

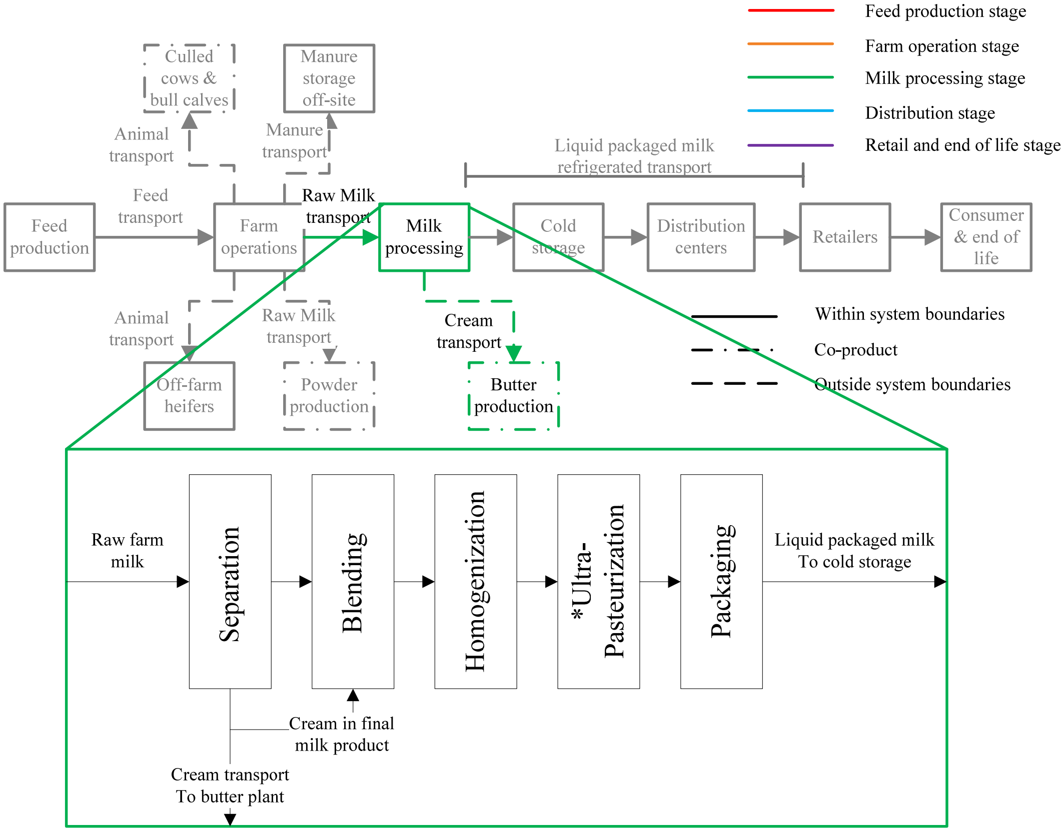

Figure 8: Process flow diagram for milk processing stage
*note 2% of the milk pasteurized during the time of this study was with the high-temperature, short-time (HTST) method

Figure 9: Location of six AOD farms and milk processing plant

Figure 10: Photograph of AOD milk plant in Platteville, CO

Figure 11: Photograph of packaging line in AOD milk processing plant

2.5. Distribution stage

All liquid milk products at the milk plant are shipped first to a nearby cold storage site and then distributed throughout the United States (Figure 12). The cold storage facility is located 34.3 miles from the milk plant, in central Colorado. Refrigerated tractor-trailer trucks travel from the milk plant to cold storage and back, continuously. AOD reserves 600 to 2600 pallet spaces at any given time at the cold storage site. After cold storage, the final liquid packaged milk is transported to customers' distribution centers throughout the United States via refrigerated tractor-trailer trucks. While each distance from cold storage to distribution centers was modeled individually, the average distance between cold storage and distribution centers servicing AOD was approximately 1,200 miles.

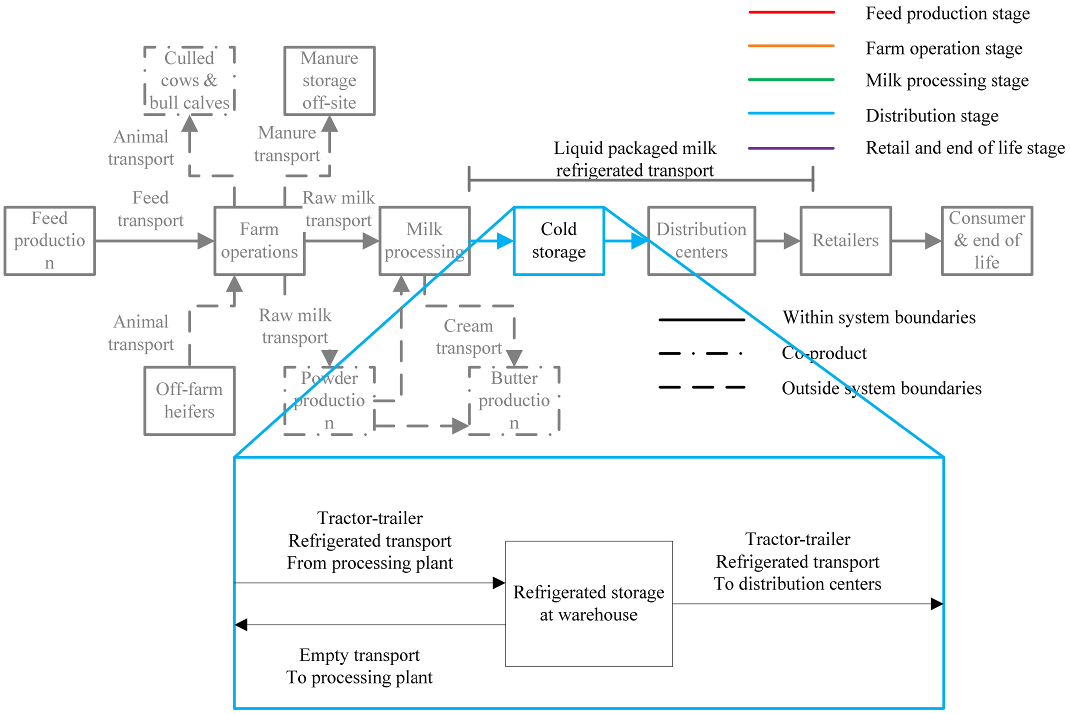

Figure 12: Process flow diagram of the distribution stage

2.6. Consumer and end of life stage

Distribution center and end of life modeling in this study is largely based on national averages and literature sources rather than primary data, and therefore, is not specific to AOD's products. Assumptions made for the distribution center through end of life system are stated in the following paragraph.

The final liquid packaged milk product is stored at distribution centers before it is transported to retail locations. All distribution center warehouse storage is refrigerated. The milk product is transported to retail locations, 50 miles on average, by refrigerated tractor-trailer trucks. The milk product is refrigerated at the retail location in vertical glass-front display cases, with two percent spoilage at retail (Economic Research Service, 1997). Consumers transport the purchased milk product on average 13.4 miles round trip (Federal Highway Administration, 2004). A 19 cubic foot refrigerator is used to store milk at the consumer's home (Brachfeld, Dritz, Keoleian, Kodama, Phipps, & Steiner, 2001). All packaging material (wood and paperboard) is assumed to be transported 10 miles to the landfill (Thorneloe, Weitz, & Jambeck, 2005). Long-distance transport of waste is not considered in this analysis. Land-filled packaging material includes wood and paper products from all processes in the liquid packaged milk life cycle. Specific paper and wood products included in land-filling are wood shipping pallets, corrugated cardboard secondary packaging, and all liquid paperboard for primary packaging including scrap primary packaging. All packaging material, including secondary and scrap packaging used at stages along the lifecycle, is assumed to be disposed of in a municipal landfill. No landfill gas recovery or recycling of packaging is considered in this analysis.

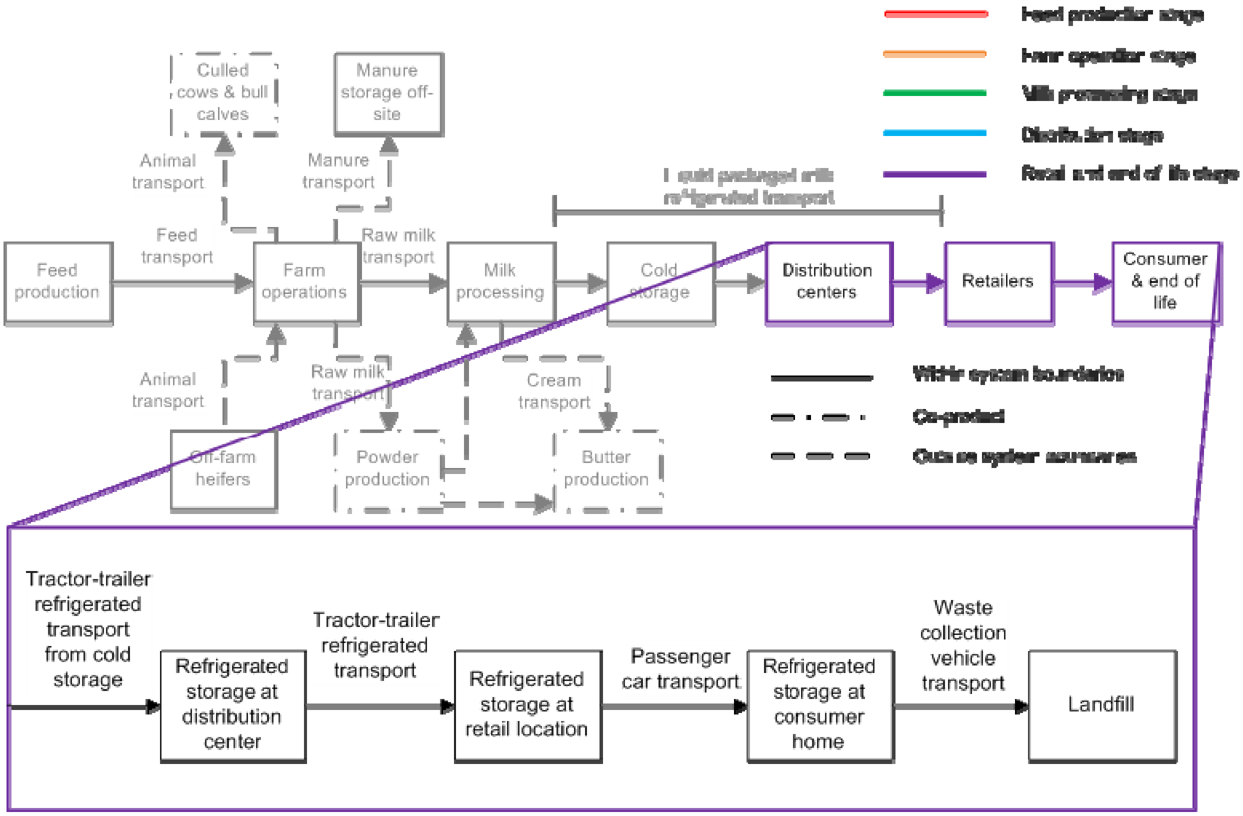

Figure 13: Process flow diagram for the retail and end of life stage

3. *Methodology*

3.1. Functional unit

The functional unit for the entire milk production system considered in this analysis is 1 gallon of packaged liquid milk purchased at retail center. "Packaged liquid milk" represents a mix of AOD's products ranging from skim to whole milk. Specifically, AOD produces skim, one percent, two percent, and whole milk. Both gallon and half-gallon products are considered in this functional unit. Results were also analyzed based on energy corrected milk (ECM) at the farm gate in order to draw comparisons to existing studies. ECM is a common correction factor for dairy products which considers the fat and protein content of the raw milk. The ECM unit considers only processes from the feed production to the farm gate, and does not include any milk processing or distribution. ECM is calculated according to Bernard (1997), using the following equation:

$$\text{ECM (kg)} = 0.3246\cdot(\text{kg}_{\text{milk}}) + 12.86\cdot(\text{kg}_{\text{fat}}) + 7.04\cdot(\text{kg}_{\text{protein}}) \quad (1)$$

3.2. Feed production stage methodology

The feed system is broken up into two main categories: feed production and feed transport. Purchased organic feed quantities and transport distances were obtained from the company's records. This analysis relied on available LCA datasets for feed production. No LCA datasets exist for U.S. organic feed production of feed types purchased by AOD. Feed production was modeled with Ecoinvent version 2.0 datasets available in SimaPro (Swiss Center for Life Cycle Inventories, 2007). LCA datasets, specifically for agriculture, are more established for European systems than those in the U.S. U.S. conventional datasets were only available for corn, soybeans, and soybean meal. The base model considered in this analysis uses U.S. conventional datasets for corn, soybeans, and soybean meal, and Swiss (CH) organic datasets for all other feed types. The base model feed datasets were chosen to represent first, geographic accuracy, and second, farming practices. Allocation for certain feed products was performed on a mass basis. Corn stalks, and other residues such as husks and leaves that may have been included in bedding shipments, were estimated at 50% of the plant weight and were therefore run with 100% allocation in SimaPro (Sawyer, 2000). Wheat midds and millet hulls were allocated as 20.5% wheat based on their percentage weight prior to milling (Anderson, 1998). Soy hulls were allocated as 8% of soybean weight (Johnson & Smith, 2003). Feed remains the most uncertain factor of this analysis. Carbon sequestration by crops was removed from the data sets as it was considered a net zero with cow respiration.

AOD feed suppliers were not contacted directly for this study. However, AOD did provide locations of feed suppliers, allowing feed transport distances to be calculated. Internet mapping systems, such as Google Maps, were utilized to make distance estimations. Feed transport was modeled using a Franklin Associates dataset for diesel tractor-trailer trucks. This dataset was chosen because it is the only U.S. dataset available for tractor-trailer transport. Additionally, this dataset includes backhaul estimates. AOD does purchase feed from two brokers for organic grain pre-mix and organic alfalfa. AOD provided basic information on the locations of the supply farms for the feed brokers; however, exact locations and numbers of supplier farms to these brokers was not available. Average distances between the alfalfa and pre-mix brokers and their supply farms were assumed to be 50 miles and 450 miles, respectively, based on general information provided by AOD.

3.3. Farm operation stage methodology

Six of AOD's farms were considered for this analysis: Coldwater, Dublin, Dipple, Ray-Glo, High Plains, and Platteville. Each of the farms was considered individually and modeled by month for this analysis. Farms were modeled by month to take into account any seasonal or scale changes over the time frame. Tours with farm managers were initially undertaken at each of the six farms to understand the overall system. Energy consumption was modeled based on utility bills and fuel usage sheets. Utility bills included municipal water, electricity, and natural gas. For all AOD facilities, GHG emissions from the grid were taken from a study done by Kim and Dale (2005) that looked at emissions on a region-by-region basis within NERC. The emissions within the ERCOT region that Dipple and Coldwater reside in were estimated to be 788.0 g CO_2e/kWh whereas the emissions within the WSCC region that the High Plains/Ray-Glo and Platteville/Plant groupings reside in were estimated to be 522.0 g CO_2e/kWh (Kim & Dale, 2005). Energy consumption for fuel types, including propane, gasoline, and diesel, were obtained from AOD's fuel usage sheets. Data was not available for on farm contract work; therefore, energy consumption from contractors was not included in this analysis. Other factors not considered in this analysis due to lack of data accessibility were animal transport between farms and manure transport to composting facilities or neighboring farms. However, animal and manure transport are of a small scale in relation to feed and final liquid packaged milk transport.

Materials used on farms were taken from AOD purchasing lists. Examples of these materials include all dairy instruments, paper towels, and all on farm chemicals. Embodied energy was determined based on farm blueprints and estimates collecting during tours of each facility. Embodied energy from farm buildings was amortized over a 50 year time period, based on construction material lifetime estimates from the (National Association of Home Builders, 2007). Farm employee transport distances were obtained from transport surveys distributed to farm managers.

All energy consumption and GHG emissions from the production of pasture are in cluded in the farm operations stage. Due to the nature of the records, pasture specific processes are unable to be parsed out from the rest of the farm operations. Diesel usage for pasture planting was calculated based on the planting area, machinery used, and plantings per year. Energy for the production of seed types used on AOD's pasture including triticale, millet, sorghum, wheat, rye, coastal grass, perennial mix, and alfalfa was also accounted for in this analysis. Modeling of diffuse on farm emissions including manure management and enteric fermentation is discussed below. Any manure inputs to the pasture are included in this modeling and incorporated in the manure management category.

3.3.1. Farm-level diffuse GHG emissions methodology

All on-farm diffuse GHG emissions were estimated using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Chapters 10 and 11. This approach outlines four sources of diffuse emissions: methane emissions from enteric fermentation, methane emissions from manure management, nitrous oxide emissions from manure management, and nitrous oxide emissions from managed soils. To accurately model these emissions sources, three important data categories need to be collected: population categories, animal feed rations, and manure management percentages. The composition and quantity of animal feed rations affect enteric fermentation as well as manure characteristics, which influence all four emissions sources. The differing animal feed rations are, therefore, used as the basis for categorizing population categories. The third important data category, manure management percentages, refers to the percentage of manure from each population category that is handled in different manure management systems. These different manure management systems, as well as the characteristics of the population categories' manure, influence emissions from all sources other than enteric fermentation. The sections below outline the methodology for establishing these data categories, and the modeling parameters for the four sources of emissions.

3.3.2. Population categories

To estimate diffuse emissions using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, the population of animals was divided into subgroups based on differing diets and management systems. AOD's records detailed population numbers for net herd, cows in milk, and total bulls by month for each farm. Of the cows in milk, 80% were considered 'high ration' and 20% considered 'low ration'. Rations were further broken down into a "high," “fresh,” or “low” ration for both females and bulls. Populations were broken up in this manner based on consultation with AOD experts.

Off-farm animal populations were also estimated based on consultation with AOD experts. The Colorado dairies were estimated to have 2200 off-farm head evenly spread into three population categories yielding approximately 733 head in each of the following categories: ‘250-500 lbs’, ‘500-900 lbs’, and ‘900 lbs+’. The modeling assumes an equivalent number of animals in the population group ‘calves’ was necessary to sustain that population. The Texas dairies were estimated to have 1100 off-farm head. The modeling assumes all 1100 were in the ‘900 lbs+’ category. The modeling, therefore, assumes an equal amount of animals in the ‘250-500 lbs’, ‘500-900 lbs’, and ‘calves’ categories were necessary to sustain the population. The populations within these categories were allocated to individual farms based on average net herd sizes of the farms.

3.3.3. Animal feed ration data

AOD ration lists were accessed and consultation with AOD experts matched population categories to the appropriate rations. ‘High bulls’, ‘low bulls’, and ‘hay bulls’ were assumed to consume ‘high ration’, ‘low ration’, and ‘dry’ diets, respectively. According to AOD experts, intake was assumed equal throughout the year, with a reduction in TMR during the growing season being off-set by the herd’s intake of pasture. A 3% loss was assumed from TMR (planned intake) to dry matter intake (DMI - actual intake) for each population. The gross energy (GE), digestibility (DE), ash content (ASH), and crude protein (CP) content were derived for each diet based on National Research Council’s Nutrient Requirements of Dairy Cattle (2001).

3.3.4. Manure management percentages

In order to estimate diffuse emissions using the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, the manure of each population category must be allocated by percentage to the appropriate manure management systems. Appendix B - Manure Management System Description [2006 IPCC Guidelines for National Greenhouse Gas Inventories] details a descriptive list of manure management systems. Based on time allocations, observations, and consultation with AOD experts, the modeling assumed 5% of manure was washed in the parlor area. Of this percentage, the separation efficiencies given in the US EPA's FarmWare Version 3.1 were used in an additive manner for any separation technologies (EPA, 2007). Settling basins, with an efficiency of 40%, were used on all farms. Incline screens, with an efficiency of 27.5%, were used at High Plains and Platteville. Vibrating screens, with an efficiency of 15%, were used at Coldwater. The percentage that passes through ends up in an uncovered anaerobic lagoon on all farms. When a farm practiced daily spread, it was assumed to occur over the non-pasture season. For example, High Plains spread 30 tons of manure per acre-year over 800 acres.

The IPCC model, however, is based on manure percentages (not totals) and volatile solids (not total manure weight). In order to determine the percentage of total manure the spreading corresponds to, the modeling assumes that volatile solids (VS) are 9.5% of total manure weight. This assumption is based on estimates from the USDA's Agricultural Waste Management Field Handbook (1999) and Midwest Plan Service's Livestock Waste Facilities Handbook (1993). Considering estimates from Coldwater records, 65% of October's manure, all of September's manure, and 10% of March's manure was spread. In order to determine the percentage of manure deposited on pasture, AOD records were used to estimate total days on pasture for both dry and lactating cows. An assumption was used, for modeling purposes, regarding the amount of time lactating cows spend on pasture. This average time allocation was used to determine a manure percentage. The time lactating cows spend on pasture varies widely depending on weather, growing season, time of year and other factors. Dry cows were assumed to be on pasture for 24 hours per day. The remaining percentage, not accounted for above, was allocated to solid storage for High Plains, Ray-Glo, and Coldwater, and to compost for Platteville, Dublin, and Dipple (High Plains began composting after the time period of analysis). Dipple uses a flush system, which, in addition to the parlor area, also passes through separation technology first. The manure of off farm animals was assumed to be handled in a dry lot system.

3.3.5. Methane emissions from enteric fermentation

Methane emissions due to enteric fermentation were estimated according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 10, using a Tier two approach. This approach develops emission factors for each population category based on GE and a methane conversion factor. A methane conversion factor of 5.5% was used based on IPCC's default value of 6.5% +/- 1.0% in conjunction with their recommendation guidance to use the lower bounds when high quality feed is available.

3.3.6. Methane emissions from manure management

Methane emissions due to manure management were estimated according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 10, using a Tier two approach. This approach develops emission factors for each population category based on volatile solids (VS) and manure management system methane conversion factors. Specific VS values were developed based on the GE, DE, and ASH content of population category feed rations using the methods previously described. The appropriate IPCC default or listed values based on region and climate were used for all other variables.

3.3.7. Nitrous oxide emissions from manure management

Nitrous oxide emissions due to manure management were estimated according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 10, using a Tier two approach. Nitrogen intake and retention must be calculated in order to develop the nitrogen excretion. To develop the nitrogen intake for each population category, the GE and CP of population category feed rations were developed using the methods previously described. To develop the nitrogen retention for each population category, consultation with AOD experts led to population category values for body weight (BW), mature weight (MW), weight gain (WG), milk production, and milk protein percentage (PR). It was assumed that an average lactating cow weighted 1,400 pounds, a bull weighed 1,100 pounds, and a calf weighed 175 pounds. The average weights of the off-farm animal categories were used. The mature weight was assumed to be 1,450 pounds. Weight gain for bulls was determined to be 1.5 pounds/day. For lactating cows, WG was calculated based on increasing in weight from 1,150 to 1,450 pounds over 750 to 800 days. The WG of calves was calculated based on increasing in weight from 100 to 250 pounds over 120 days. The WG of off-farm animals was calculated based on increasing in weight from 250 to 1,100 pounds over 18 months. Milk production was estimated to be 70 pounds per day for high/fresh cows and 30 pounds per day for low cows. The PR was assumed to be 3% based on AOD records. Using the developed nitrogen intake and nitrogen retention values, nitrogen excretion values were determined according to the IPCC methodology. Nitrogen losses due to runoff from dry lot and solid storage were also calculated assuming a 4%

nitrogen loss value based on the IPCC range and listed studies for dry climates. The appropriate IPCC default or listed values based on region and climate were used for all other variables.

3.3.8. Nitrous oxide emissions from managed soils

Nitrous oxide emissions occur from the application of animal manure to fields (daily spread) as well as from manure deposited on pasture by grazing animals. In order to properly report values for daily spread of animal manure, it was necessary to estimate the manure nitrogen available for application according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 10. The nitrogen content of the bedding for maternity pens was considered to be 7 kg N per animal-year based on listed studies in the IPCC Guidelines (note: only Coldwater and High Plains applied daily spread). Similarly to N_2O emissions from manure management, direct emissions, indirect emissions, and nitrogen losses due to leaching were considered for N_2O emissions from managed soils. These emissions were estimated according to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 11, using a Tier two approach. The appropriate IPCC default or listed values based on region and climate were used for all other variables.

3.4. Milk processing stage methodology

The processing system includes raw milk transport, packaging production, and all milk plant operations. Primary data was collected for all stages in the milk processing system. Utility bills, including natural gas, electricity, and water were obtained from AOD’s records. Quantities of materials for plant embodied energy were acquired from actual blueprints, plant tours, and data from the packaging line supplier, Tetrapak. Material datasets for embodied energy were modeled based on existing Simapro datasets, which include Steel Fe470 I (IDEMAT, 2001)

Rubber SBR FAL (Franklin Associates, 1998), Stainless Steel X5CrNi18 (304) I (IDEMAT, 2001), Concrete (reinforced) I (IDEMAT, 2001), Fibre Glass (Swiss Center for Life Cycle Inventories, 2007), and Copper Cu-EI (IDEMAT, 2001). Embodied energy values were amortized over the useful life of each construction material. In addition to the processing plant, the material and energy inputs to the corporate office were considered as well as all employee transportation related to the business. Corporate office supplies and utilities were derived from purchase lists and utility bills. The portion of embodied energy in the corporate office was estimated based on the fraction of the office building occupied by AOD. Employee travel surveys, which covered travel to and from work as well as any business travel, were distributed within AOD to estimate the distance and mode of employee transportation activities.

Other important emissions from processing include chemical usage, purchased items, and milk plant industrial wastewater. All industrial chemicals used in the milk plant were inventoried. Important USDA organic-approved plant chemicals include acetic acid 98%, amino-ethanol, phosphoric acid, sodium hypochlorite 15%, propanol, hydrogen peroxide 50%, methylpentane, and certain organic chemicals. All chemicals were modeled using Ecoinvent datasets in Simapro according to the chemical concentrations. Other plant purchased items, including paper towels and steel instruments, were also included in this analysis. AOD has an on-site aerobic industrial wastewater treatment facility. The wastewater treatment process was modeled after a well-managed aerobic system based on 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 6 for industrial wastewater treatment. To calculate wastewater emissions chemical oxygen demand (COD), quantity of wastewater, and quantity of sludge were all obtained directly from AOD. All other values used to calculate wastewater emissions were obtained directly from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories.

To assess packaging quantities, AOD plant employees weighed certain secondary and primary packaging including plastic wrap, tape, and glue. Additionally, weights of primary packaging were obtained from a central AOD electronic database. Weights of each packaging type can be seen in Table 3. Plant employees estimated a shrinkage rate of approximately 2-3% for all packaging materials purchased.

Table 3: Weights of primary and secondary packaging

Packaging type	Weight (lbs)
Pallet	63.5
Gallon	0.141
Half-gallon	0.131
H.G Cap	0.0015
Plastic Wrap (3 CT/6 CT)	0.0008/0.0004
Tape (3 CT)	0.0044
6 CT Corrugated Cardboard	0.556
3 CT Corrugated Cardboard	0.406
4 CT Corrugated cardboard	0.974

3.5. Distribution stage methodology

The quantity of space rented on average by AOD at the cold storage site was obtained through communications with the cold storage facility located near Denver, CO. The electricity use for refrigeration was based on Franklin Associates values for warehouse refrigerated storage (Franklin Associates, 2007). The cold storage facility is located in Central Colorado; therefore, the electricity generation was modeled based on the Western Systems Coordinating Council (WSCC) electrical grid (Kim & Dale, 2005). Distances between cold storage and distribution centers were obtained through AOD's shipping records. Transport was modeled using a tractor-trailer truck dataset from Franklin Associates. Backhaul is included in the Franklin Associates dataset. AOD had no access to exact truck routes; thus, the most direct routes to distribution centers were modeled using Google maps. All transport units were in ton-miles; therefore, number of trips to distribution centers did not need to be modeled. Because transport was modeled using ton-miles, idle time was also not accounted for in this study.

3.6. Consumer and end of life stage methodology

Modeling of the consumer and end of life system was based on national averages and literature sources rather than primary data. Distribution center refrigeration was modeled using refrigerated warehouse values from Franklin Associates and based on the average U.S. electric grid (Franklin Associates, 2007). Refrigeration at retail was modeled using refrigerated retail values from Franklin Associates for vertical glass display cases, and based on the average U.S. electric grid from Franklin Associates for the late 1990s. A sampling of AOD distribution centers and the main retail locations they serviced were mapped using internet mapping systems such as Google Maps to make an estimate of transport distances to the retail location. Transport distances from distribution to retail locations varied greatly, but averaged 50 miles. There is no existing literature indicating a standard distance from distribution centers to retail locations; therefore, the average of 50 miles was assumed for this analysis. Such transport was modeled using Franklin Associates data for tractor-trailers, the same dataset used to model transport from cold storage to distribution centers. Refrigerated transport was assumed to add 1.89 liters of diesel per hour for transport to the retail location.

Consumer transport distance was assumed to be 13.4 miles roundtrip based on the National Transportation Survey assuming the purpose of shopping (Federal Highway Administration, 2004). The percentage of this distance allocated to milk was based on economic data. Per capita consumers were assumed to purchase 19.5 gallons of milk per year (CNPP, 2006) at \$3.19 USD per half-gallon according to AOD milk on the shelf in March 2008 (\$6.38 USD per gallon). The average per capita amount spent on groceries was assumed to be \$267 USD per month (Economic Research Service, 2005). It is likely that purchasers of organic milk spend more per capita on groceries than the average American, but no data on the monthly spending for organic shoppers was available. It is possible this price inconsistency could lead to higher than actual consumer transport values. It was assumed that only one gallon of milk was purchased per grocery visit. Consumer transport was based off an economic allocation with purchasing milk accountable for 3.87% of the entire grocery trip. The calculations for the economic allocation are as follows:

$$\text{cost of milk/gallon (gallon purchased/12 months)} = \text{cost of milk/month} \qquad (2)$$

$$\text{cost of milk per month/cost of groceries per month} = \text{allocation of grocery trip to milk} \qquad (3)$$

Following these calculations, it was assumed that milk is responsible for .52 mi of the grocery trip. Consumer refrigeration was based on a past LCA conducted by the Center for Sustainable Systems for Stonyfield Yogurt (Brachfeld, Dritz, Keoleian, Kodama, Phipps, & Steiner, 2001). This study assumed a 19 ft^3 refrigerator with 10 ft^3 of empty space. A ratio of the empty refrigerator space based on the volume of the milk as compared to the rest of the refrigerator contents was allocated to the milk, as was done in the Brachfield et al. 2001 study. Not allocating this empty refrigerator space to the milk would decrease the consumer electricity quantity 53%. Again, Franklin Associates data for the average U.S. electric grid was utilized for consumer refrigeration. Waste management transport distances were assumed to be approximately 10 miles, based on a previous study, as the actual waste management transport values are unknown (Thorneloe, Weitz, & Jambeck, 2005). Waste management transport values were based solely on the weight of the HDPE gallon and plastic coated paperboard half-gallon packaging material, with the assumption that all milk was consumed or disposed of at the consumer location. Long-distance waste transport was not considered in this analysis. It was assumed that all primary plastic coated paperboard for half-gallons and HDPE for gallons was land-filled and no recycling was considered. Past literature has found that recycling of milk cartons is negligible (EPA, 2000). Only wood and paper based products were modeled for landfill methane emissions, as only biogenic materials release methane as they decompose. Such paper products include waste from wooden shipping pallets, corrugated cardboard for storing milk products and packaging products (secondary packaging), and the plastic coated paperboard (primary packaging). Landfill GHG emissions were modeled based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 3 model for a well-managed landfill in the U.S. Land-fill gas recovery was not considered in this analysis.

3.7. Allocation methodology

3.7.1. Bull calves and culled cows

In previous studies, allocation between meat (bull calf and culled cow) and milk co-products has been based on economics (Hospido, Moreira, & Feijoo, 2003); (Thomassen, Calker, Smits, Iepema, & de Boer, 2008); (Grönroos, Seppala, Voutilainen, Seuri, & Koikkalainen, 2006) mass (Grönroos, Seppala, Voutilainen, Seuri, & Koikkalainen, 2006) or (Casey & Holden, 2005); (Cederberg & Mattsson, 2000). This study, used a causal relationship based on the energy (in the form of feed) needed to produce the meat co-product.

Bull calves are sold shortly after birth on AOD farms. The net energy requirement for pregnancy was calculated using equation 2-19 from National Research Council's Nutrient Requirements of Dairy Cattle 2001, based on an average calf birth weight of 45 kilograms (see Appendix C: Net Energy Requirement for Pregnancy Equation [National Research Council 2001]for equation). The amount of feed required to supply the net energy requirement for pregnancy was determined based on a general value of 18.50 MJ per kilogram of feed from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 10. The proportion of different feedstuffs from that total feed amount was based on a typical cow diet as identified by consultation with AOD experts. All energy and GHG burdens from the production of these feedstuffs were then subtracted from the liquid milk system. In this way, only the feed burdens required to provide the additional energy to produce the calf are allocated to it when sold.

For allocation of end-of-life culled cows, the feed burden equivalent to the embodied energy in the empty body mass of culled cows are allocated to them. Assuming a 635 kg cow with a body condition score of 3, Table 2-4 from National Research Council's Nutrient Requirements of Dairy Cattle (2001) estimates the cow's empty body mass to be 18.8% fat and 16.8% protein, with the remaining percentages composed of ash and water. Fat and protein are assumed to be the primary energy embodiment of the cull cow; using energy densities obtained from National Research Council's Nutrient Requirements of Dairy Cattle 2001 (9.4 Mcal/kg for fat and 5.6 Mcal/kg for protein) an embodied energy for the cull cow is estimated. The amount of feed required to equate the empty body mass energy was determined based on a general value of 18.50 MJ per kilogram of feed from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Chapter 10. The proportion of different feedstuffs from that total feed amount was based on a typical cow diet as identified by consultation with AOD experts. All energy and

GHG burdens from the production of these feedstuffs were then subtracted from the liquid milk system. This methodology assumes that the feed burdens allocated to the culled cow only relates to the embodied energy within that cow. Any energy for conversion, respiration, maintenance, necessary for the continued life and milk production of that cow was not included in the allocation.

3.7.2. Butter, powder, 3rd party cream

While the majority of raw milk produced on AOD's farm is packaged and sold as milk, a small amount of raw milk is used to create skim milk powder. Any milk powder that is sold as milk powder, rather than mixed back into liquid milk, is considered to be out of the system, with any impacts associated to the raw milk used for producing this powder allocated away from the milk life cycle on a milk solids basis (Feitz, Lundie, Dennien, Morain, & Jones, 2007). The GHG emissions and energy associated with the milk powder is subtracted only from the farm and feed stages.

At the milk processing plant all raw milk is first separated into cream and skim milk. Next, the cream is blended back into the skim milk to create the different milk fat products (i.e. 1% milk, 2% milk). Excess cream is either transported to a co-packer or converted into butter or sold to a third party as cream. Similar to the milk powder, burdens associated with excess cream shipped from the milk plant to a butter co-packer or to a third party are allocated away from the fluid milk life cycle on a milk solids basis. All GHG emissions and energy associated with the raw milk and cream leaving the systems was subtracted from the farm and feed stage. This method equated to allocating approximately 22% of the total GHG emissions and energy consumption from the feed and farm stages to butter, powder, and 3rd party cream.

3.7.3. Manure allocation

In this study, all emissions associated with manure was considered a consequence of the milking system and, therefore, attributed to the milk life cycle. However, if manure created on AOD's farms was spread on non-AOD fields, the emission were considered out of the system and not added into the analysis.

3.8. Model description

This dairy GHG and energy model was constructed using the LCA software SimaPro 7.1.6 in accordance with the ISO 14040 LCA standards (ISO, 1997). Whenever possible, primary data was used as inputs into the model. In certain cases, best estimates were made based on literature values including feed production and all data in the system past the distribution centers. Simapro Method's IPCC 2007 GWP 100a version 1.0 and Eco-indicator 95 version 2.04 were used to analyze GHG emissions and energy consumption respectively.

3.9. GHG model

The GHG model for this study is based on life cycle greenhouse gas emissions. Greenhouse gases included in this analysis are nitrous oxide, carbon dioxide, and methane. All GHGs have been normalized to carbon dioxide equivalents. GHG emissions due to enteric fermentation, manure management, industrial wastewater treatment, and solid waste management were estimated according to chapters 10, 11, 6, and 3 respectively, of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories. The 100-year time horizon global warming potentials (GWP) for methane and nitrous oxide were used in the model (IPCC, 2007). GWP values utilized in this study can be seen in Table 4. Simapro's method IPCC 2007 GWP

100a was used to assess the life cycle GHG impacts of milk production. This method does not include or take into account indirect formation of nitrous oxide from nitrogen emissions, radiative forcing due to emissions of NO_x, water, sulphate in the lower stratosphere and upper troposphere, or CO_2 formation from CO emissions.

Table 4: Lifetime and GWP of greenhouse gases utilized in this analysis (IPCC, 2007)

GHG	Lifetime (yrs)	GWP 100 yr time horizon
Carbon Dioxide (CO2)	X	1
Methane (CH4)	12	25
Nitrous Oxide (N2O)	114	298

3.10. Energy model

The energy model for this study is based on primary energy. Primary energy includes total fuel cycle energy (upstream and combustion) as well as material production energy (feedstock energy, process/fuel energy). When comparing energy values from this study with previous studies it is critical that the energy accounting method be the same. Simapro's method Eco-indicator 95 version 2.04 [characterization energy resources (LHV)] was used to assess the life cycle energy impacts of milk production.

3.11. Data categories

This study analyzed many inputs into the milk production life cycle. To display results effectively, all processes analyzed have been grouped into categories. Table 5 lists the specific processes included in each category of this analysis.

Table 5: Break-down of data categories

Category	**Includes**
Feed production	Inputs into production of feed and bedding, excluding pasture operations
Feed transport	Feed and bedding transport from all supply farms and brokers to the six farms
Enteric fermentation	Cow enteric fermentation
Manure management	Manure management and managed soils
Farm management	Natural gas, propane, diesel, gasoline, electricity, water usage at farms, pasture planting/cutting
Raw milk transport	Transport of raw milk from the six farms to the milk plant, transport of raw milk used for powder and then added back into CA milk (to and from powder co-packer)
Dairy plant utilities	Plant natural gas, electricity, water, and wastewater treatment
Milk packaging	All primary and secondary packaging including scrap
Product storage and transport	Transport of milk to cold storage from plant, transport of empty tractor trail truck from cold storage to plant, refrigeration of milk at cold storage, transport of milk from cold storage to distribution centers
Building embodied energy	All farm, plant, and corporate office building materials
Dairy supplies	All miscellaneous purchased items including plant and farm chemicals, paper towels, plant, farm, instruments and office supplies
Employee transport	Transport of employees to and from work as well as business travel. Transport includes bus, car, and plane.
Corporate office	Corporate office electricity, natural gas, and water usage. Corporate office supplies.
DC refrigeration and transport	DC refrigeration and transport from DC to retail center
Retail refrigeration	Retail refrigeration
Consumer transport	Consumer transport
Consumer refrigeration	Consumer refrigeration
Landfill	Waste management transport, landfill gas from wood and paper products

4. *Results*

4.1. Base model results

Model results on a functional unit basis are shown in Table 6 and Table 7. For raw milk at the farm gate, 1.35 kg CO_2e were emitted and 5.19 MJ (0.12 gallons of gasoline equivalent

LHV) of energy were consumed per kg of ECM. Over the full liquid milk life cycle, 7.98 kg CO_2e were emitted per gallon of packaged liquid milk, and the full life cycle energy consumption was 72.6 MJ/gallon (1.65 gallons of gasoline equivalent LHV). Detailed results with allocation methodology can found in Appendix A – Detailed Results.

Table 6: GHG emission and energy consumption per volume of packaged liquid milk

	Energy Consumption	GHG Emissions
Per Gallon	72.6 MJ	7.98 kg CO_2e

Table 7: GHG and energy consumption per ECM at the farm gate

	Energy Consumption	GHG Emissions
Per kg ECM	5.19 MJ	1.35 kg CO_2e

4.2. Life cycle distribution of GHG emissions

174,000 tons of CO_2e were emitted for the entire milk production life cycle over the time frame of analysis. GHG emissions by individual processes in the milk production system are shown in Figure 14. Methane produced during enteric fermentation contributes the greatest emissions on a CO_2e basis, accounting for 25% of total system GHGs. Organic feed production is the next largest contributor, making up 17% of total GHG emissions, with feed transport contributing 7% to total GHG emissions. Manure management also accounts for 6% of total emissions. The other large GHG contributor to the system is final product storage and transport, which accounts for 11% of total emissions.

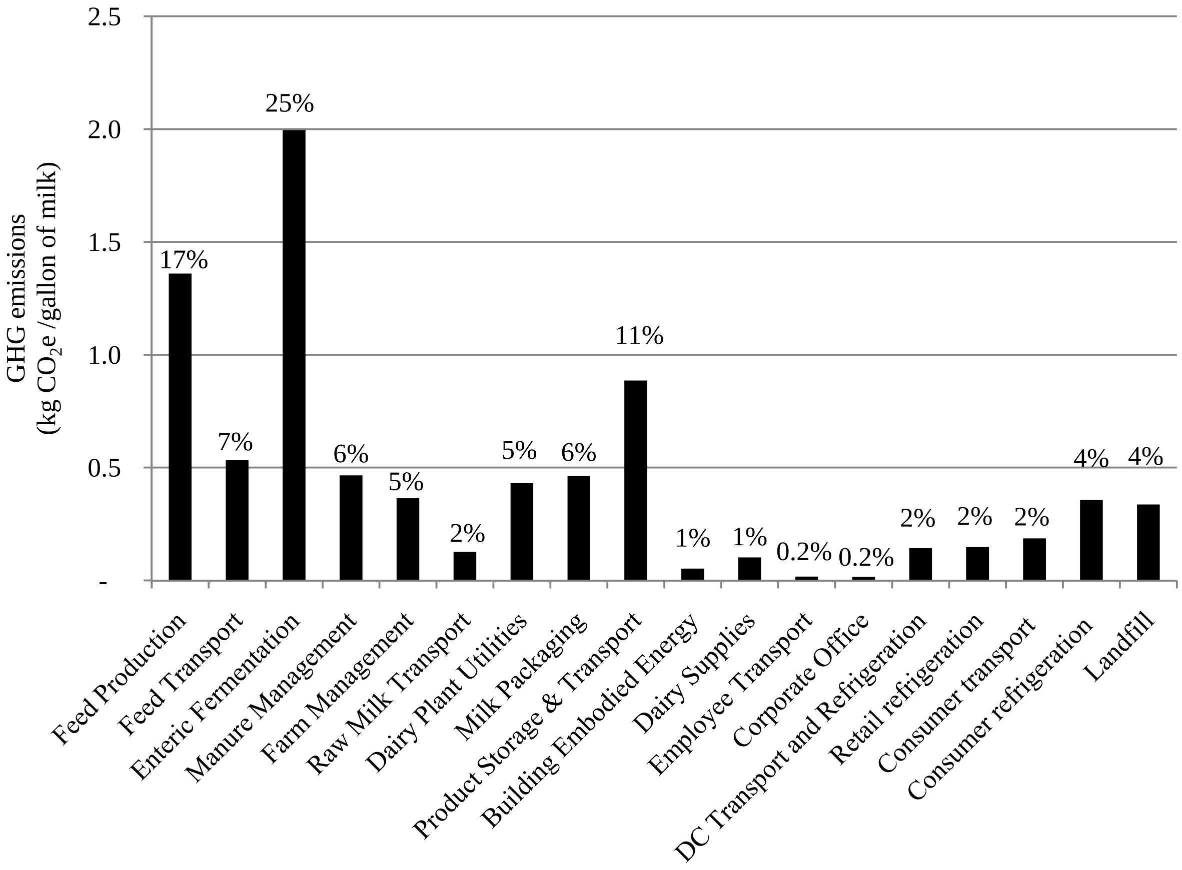

Figure 14: Distribution of life cycle GHG emissions for one gallon of packaged liquid milk

4.3. Life cycle distribution of energy consumption

Across the entire milk production life cycle for the time frame of analysis 1,590,000 GJ (36,100 gallons of gasoline equivalent LHV) of energy was consumed. Nonrenewable energy sources account for approximately 93% of total milk life cycle energy consumption. Energy use by individual processes in the milk production system per functional unit is shown in Figure 15. Product storage and transport is the largest energy input, accounting for 15% of all energy usage. Both feed production and product packaging each account for 14% while transportation of feed from supplier farms to AOD farms accounts for 10% of the total milk life cycle energy consumption. Farm management makes up 10% of total energy usage; whereas, dairy processing plant utilities account for 12% of total energy usage.

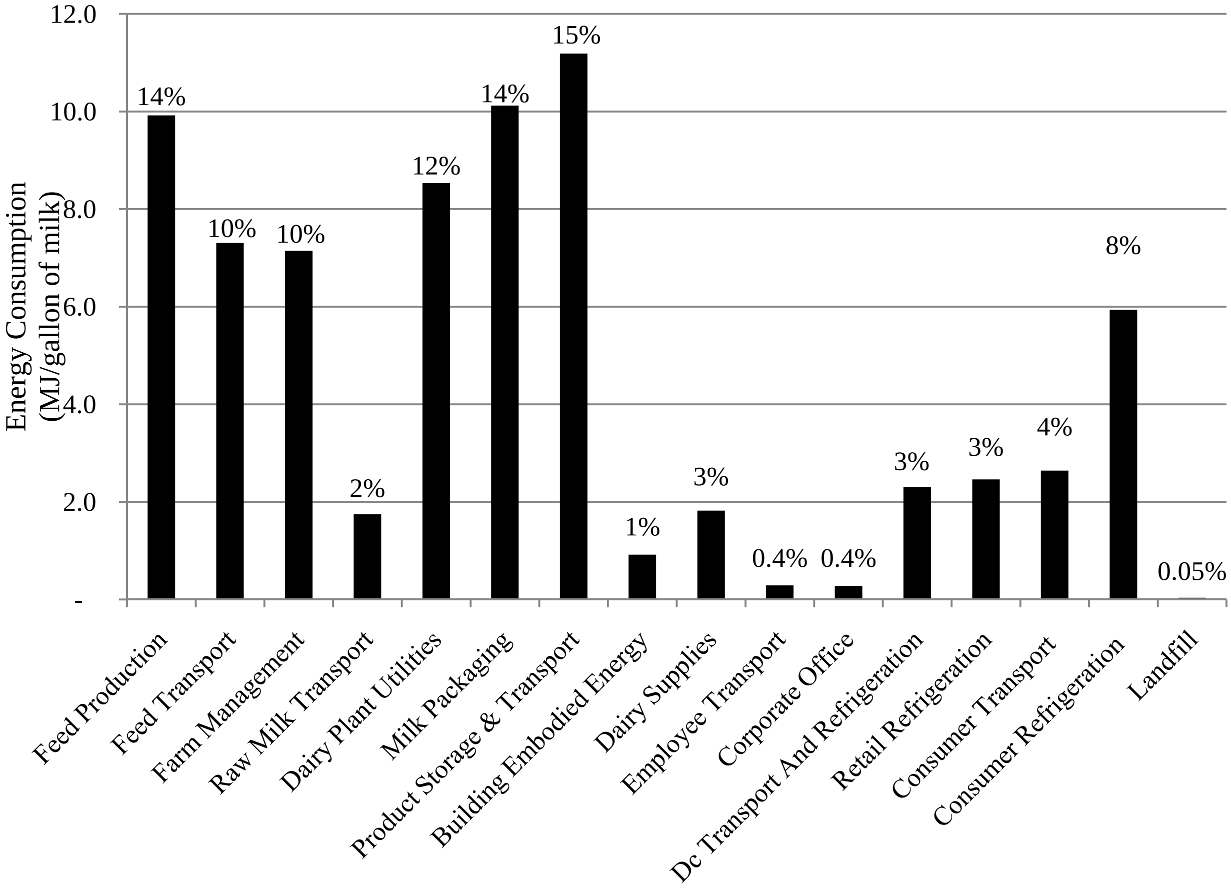

Figure 15: Distribution of life cycle energy consumption for one gallon of packaged liquid milk

4.4. Feed production stage results

Feed for the livestock is a major contributor to the GHG emissions across the milk life cycle. The feed production stage emitted 41,300 tons of CO_2e over the time frame of analysis, which is 24% of total emissions across the milk life cycle. Production of the actual feed and feed transport made up the majority of these emissions, 71% and 28% respectively (Figure 16). The feed production stage consumed 375,000 GJ (8,520 gallons of gasoline equivalent LHV) of energy over the time frame of analysis, and contributed 24% of energy usage across the milk life cycle. Again, production of the cattle feed and feed transport were the largest energy consumers in the feed production stage, accounting for 57% and 42% of the energy usage (Figure 17).

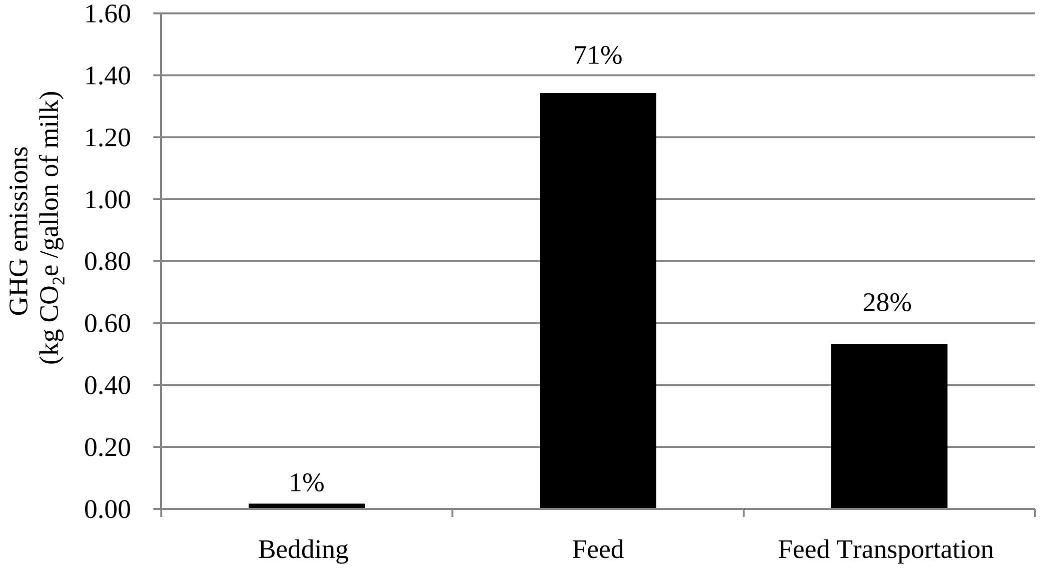

Figure 16: GHG contributions from the feed production stage

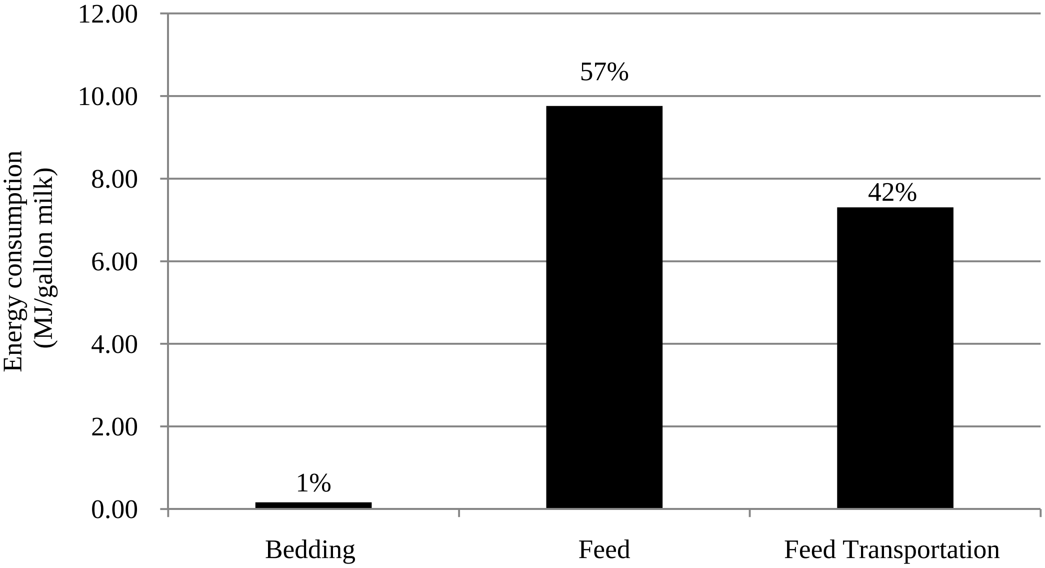

Figure 17: Energy consumption across the feed production stage

4.5. Farm operations stage results

The farm operations stage emits the largest amount of GHGs in the milk life cycle. The farm emits 64,900 tons of CO_2e or 37% of total emissions over the milk life cycle. Of these emissions, cow enteric fermentation is by far the largest emitter contributing 67% of on farm emissions (Figure 18) or 25% of total emissions across the milk life cycle. Additionally, the farm consumes 214,000 GJ (4,860 gallons of gasoline equivalent LHV) or 14% of total energy across the time frame of analysis. The largest energy consumer in the farm operations stage is electricity, accountable for 43% of energy consumption (Figure 19).

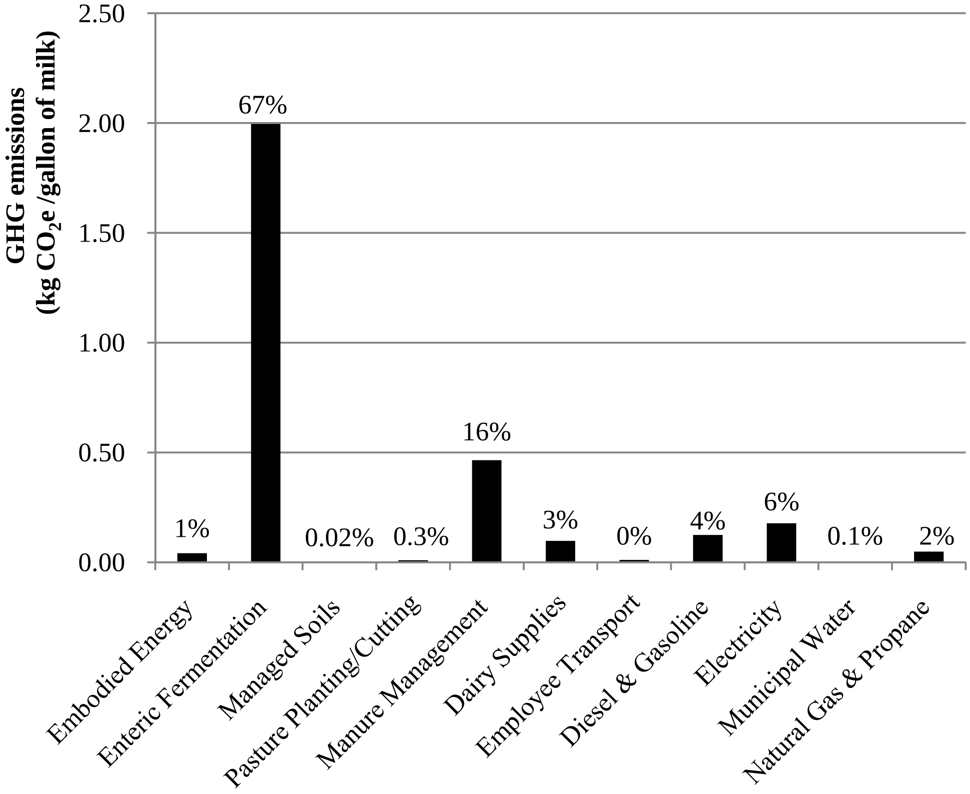

Figure 18: GHG contributions from the farm operations stage broken down by process

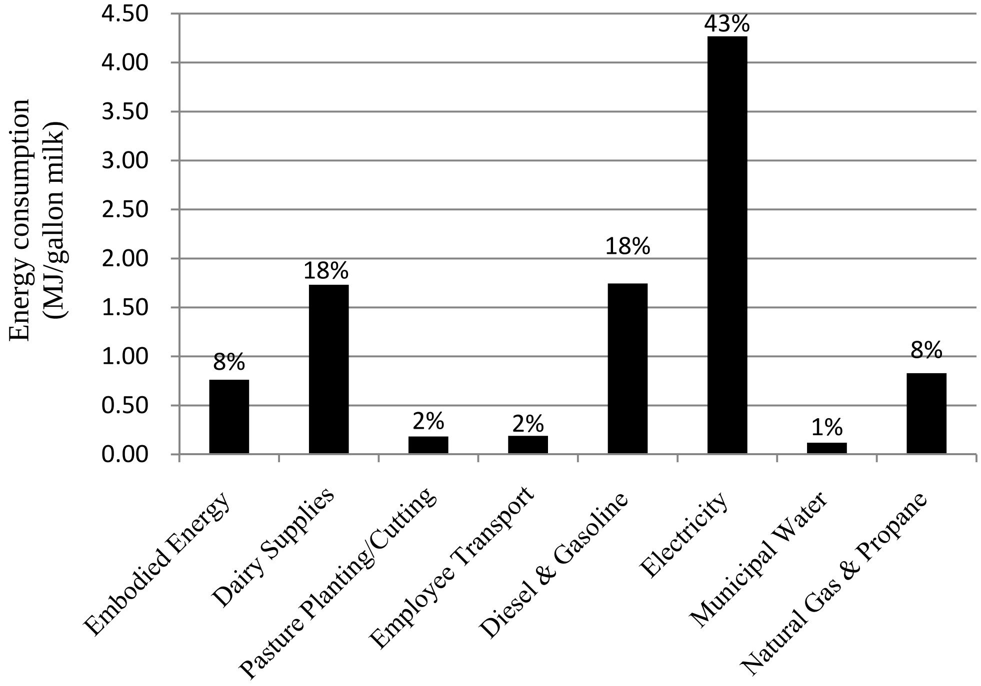

Figure 19: Energy consumption from the farm operations stage broken down by process

4.6. Comparison between the six farms

The GHG emissions per ECM are different between the six farms (Table 8). As can be seen below, Dipple has the highest emissions at 1.96 kg CO_2e/kg of ECM and High Plains has the lowest emission with 1.10 kg CO_2e/kg of ECM. These figures include milk transport to the plant (Table 8). Results at the farm gate versus results with milk transport to the plant only change significantly for the three Texas farms (Table 8).

Three processes that differ greatly between the six AOD farms are feed transport to the dairy farm, raw milk transport from the farm to the milk plant, and manure management. Raw milk transport emissions per ECM is much greater for the Texas farms than for the Colorado farms, as the Colorado farms are all closer to the milk plant (Figure 20). Specifically, raw milk transport for the Platteville farm is negligible, as it is located adjacent to the milk plant. Feed transport is approximately equivalent for all of the farms, except Dipple and Dublin, for which it is significantly higher, as these farms are furthest from the main feed suppliers in Idaho and the panhandle of Texas. Manure management is over nine times greater for Dipple than any of the other farms due to its largely liquid based manure handling technique as opposed to the solid manure handling technique applied on the other five farms (Figure 20).

Table 8: Emissions per ECM for each of the six farms and overall, both at farm gate and including raw milk transport

	Emissons with raw milk transport (kg CO2e/kg ECM)	Emissions at farm gate (kg CO2e/kg ECM)
High Plains	1.10	1.10
Platteville	1.23	1.23
Ray-Glo	1.13	1.12
Dipple	1.96	1.88
Dublin	1.55	1.48
Coldwater	1.46	1.41
Overall	1.38	1.35

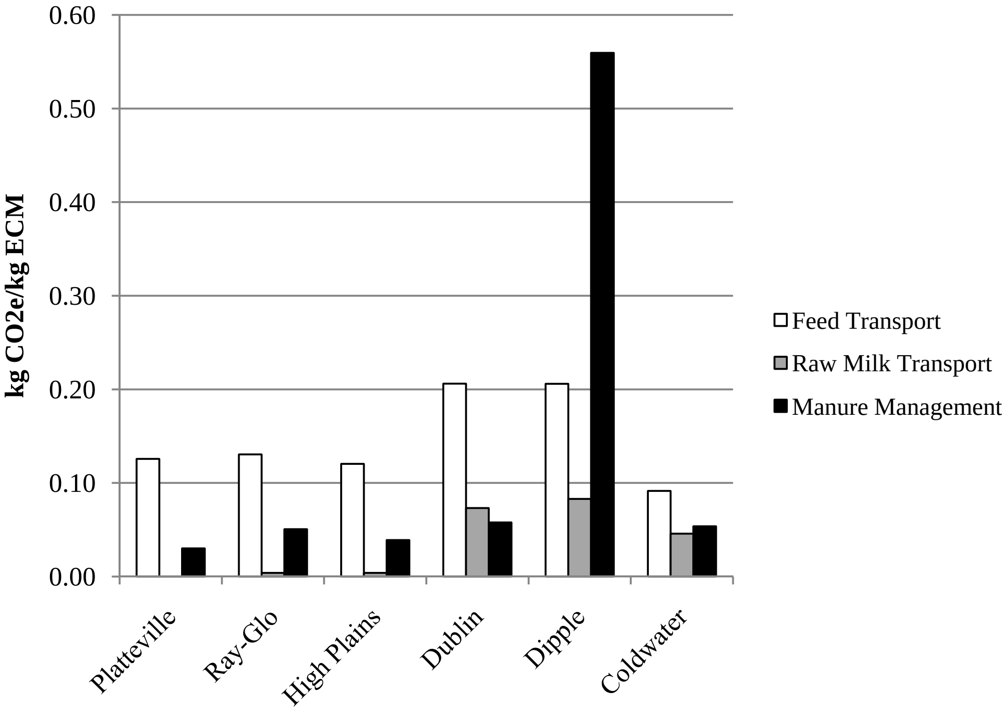

Figure 20: Comparison of raw milk transport, feed transport, and manure management for the six AOD farms based on the kg ECM produced at each farm

4.7. Milk processing stage results

The milk processing stage contributes 23,100 tons of CO_2e, or 13% of CO_2e over the milk life cycle, and consumes 456,000 GJ (10,400 gallons of gasoline equivalent LHV) of energy over the entire milk life cycle for the analysis time frame. Milk packaging and dairy plant utilities contribute the most GHGs and consume the most energy of all processes in the milk processing stage. Packaging accounts for 44% of milk processing stage GHG emissions (Figure 21), and 48% of milk processing energy consumption (Figure 22). Dairy plant utilities account for about 41% of both GHG emissions and energy consumption in the milk processing stage (Figure 21, Figure 22). Overall, the milk processing stage contributes 29% of the energy consumption and 13% of the GHG emissions for the total milk life cycle.

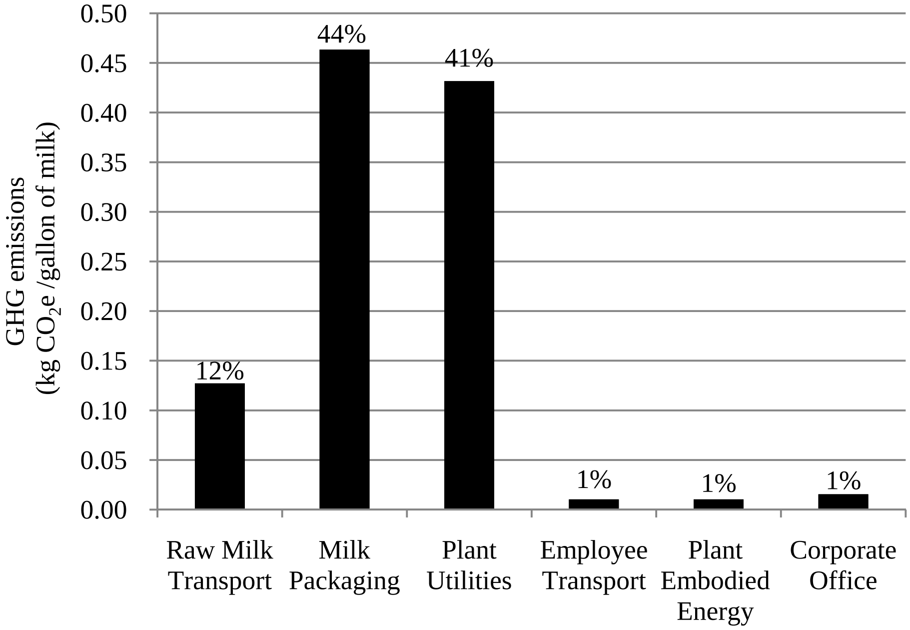

Figure 21: Break-down of GHG emission contributions from the milk processing stage

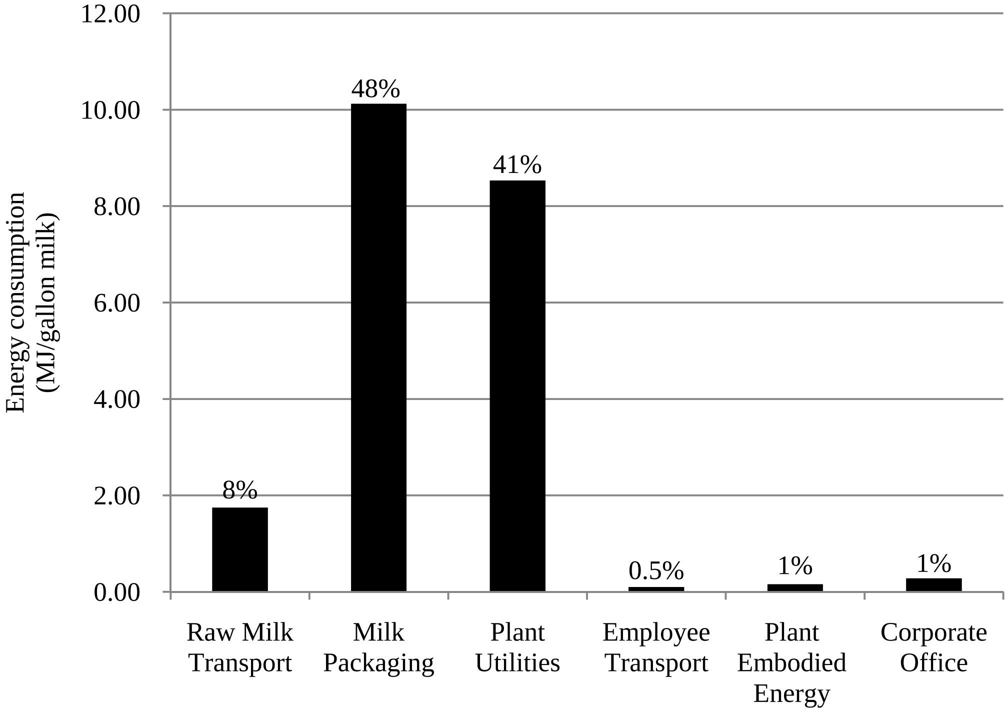

Figure 22: Break-down of energy consumption from the milk processing stage

4.8. Distribution stage results

The distribution stage contributes 16,300 tons of CO_2e or 9% of total GHG emissions to the overall milk life cycle for the time frame of analysis. Transportation from cold storage to distribution centers across the country represents the largest contribution of GHGs, 86% of the distribution stage (Figure 23). Additionally, refrigeration at cold storage contributes 11% of the GHGs to the distribution stage (Figure 23). The distribution stage also consumes 241,000 GJ (5,500 gallons of gasoline equivalent LHV) of energy over the entire milk life cycle for the time frame of analysis or 15% of total energy consumption. Again, transportation from cold storage to distribution centers across the U.S. consumes the largest amount of energy over the distribution stage, 80% (Figure 24).

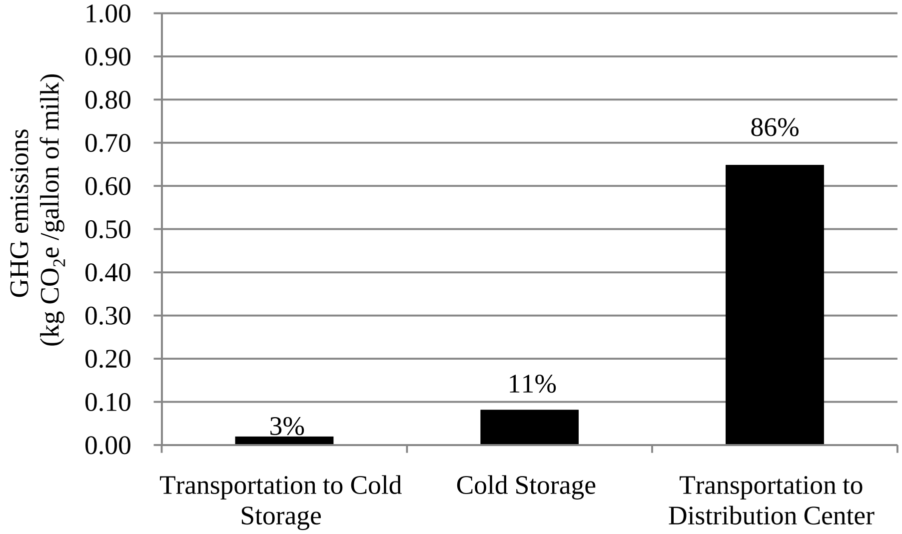

Figure 23: Break-down of GHG emission contribution from processes within the distribution stage

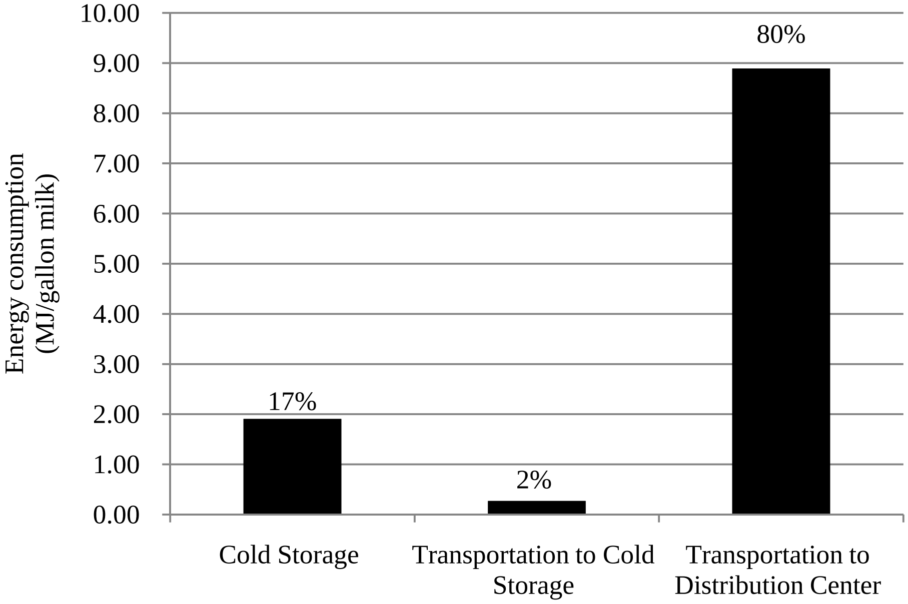

Figure 24: Break-down of energy consumption from processes within the distribution stage

4.9. Consumer and end of life stage results

The retail, consumer, and end of life stages for liquid packaged milk account for 25,500 tons CO_2e or 15% of the total GHG emissions of the milk life cycle. Consumer refrigeration contributes the largest quantity of GHGs to this stage, with 30% of the GHG emissions (Figure 25). Methane released from landfill disposal of paper and wood packaging products adds about 29% to the consumer and end of life stage GHG emissions (Figure 25). Overall, the consumer is accountable for 11,900 tons or 7% of the CO_2e released over the milk product life cycle (including consumer transport and refrigeration). Approximately 292,000 GJ (6,600 gallons of gasoline equivalent LHV) of energy are consumed annually for this stage of the milk system, with about 44% of this energy usage occurring during consumer refrigeration (Figure 26).

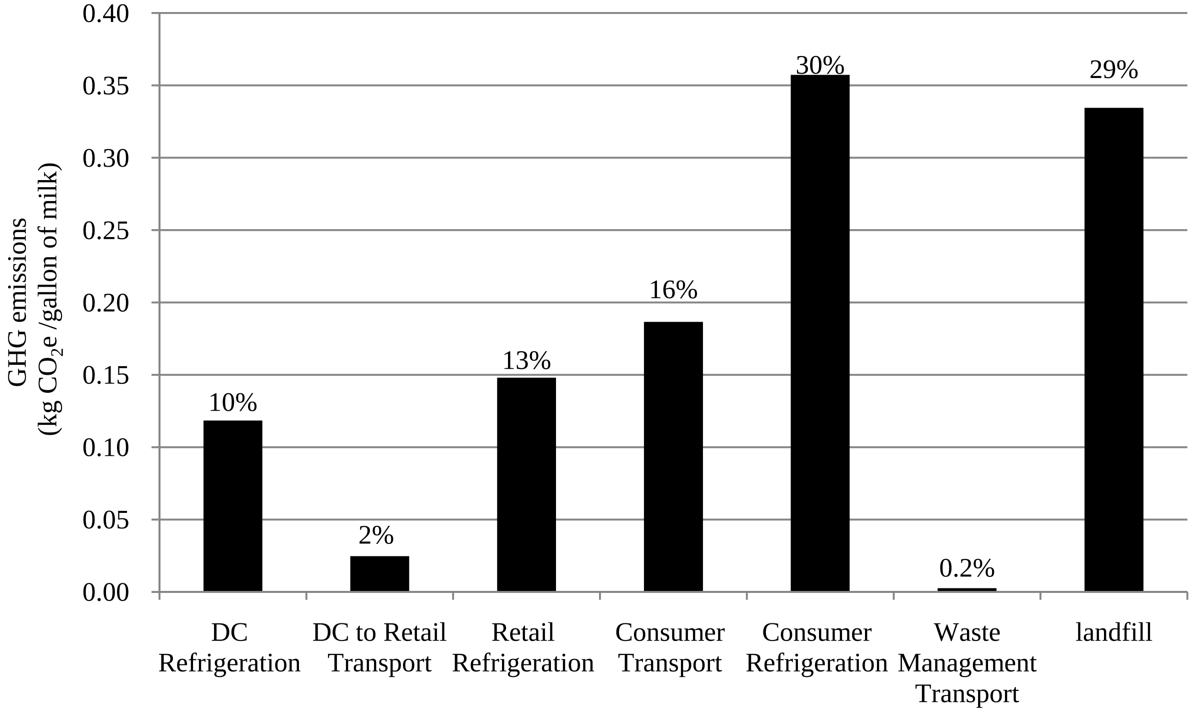

Figure 25: Break-down of the consumer and end of life stage GHG contributions by process

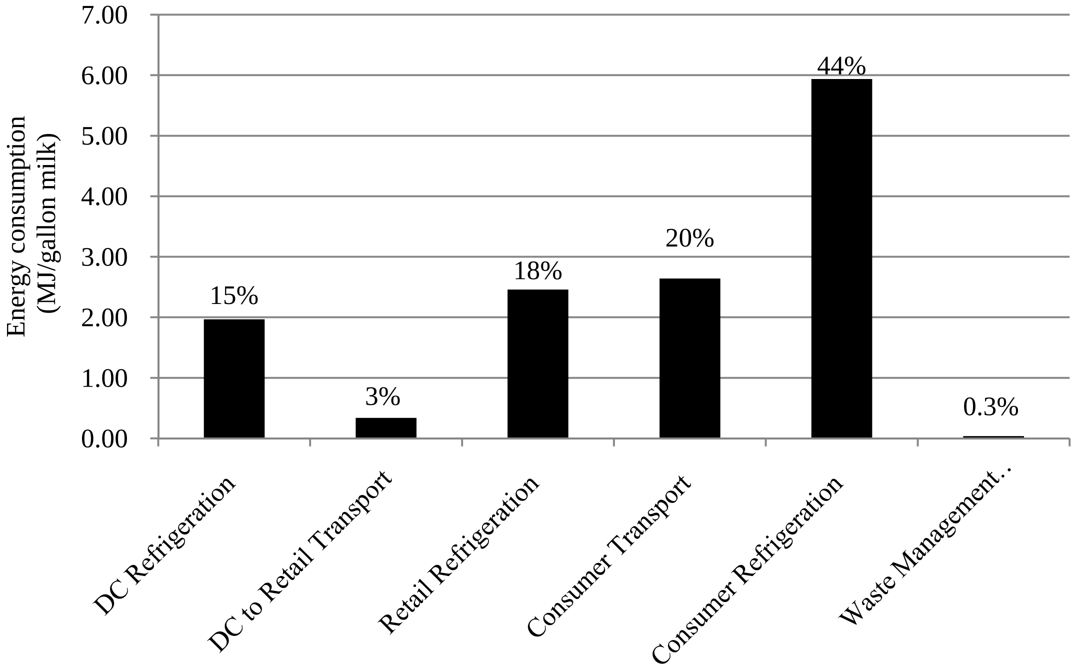

Figure 26: Break-down of the consumer and end of life stage energy consumption by process

4.9. Transportation results

Transportation occurs at many stages in the milk life cycle including feed transport, raw milk transport, and transport to distribution centers. Overall, transportation contributes 40,200 tons CO_2e or 23% of GHG to the entire milk life cycle. Transportation from cold storage to distribution centers throughout the country is the largest transportation GHG emmitter, accounting for 35% of transportation GHGs (Figure 27). Transport across all processes also consumes approximatley 468,000 GJ (10,600 gallons of gasoline equivalent LHV) or 30% of total energy consumption over the milk life cycle, with transport to distribution centers again accounting for the greatest portion of this consumption, 41% (Figure 28).

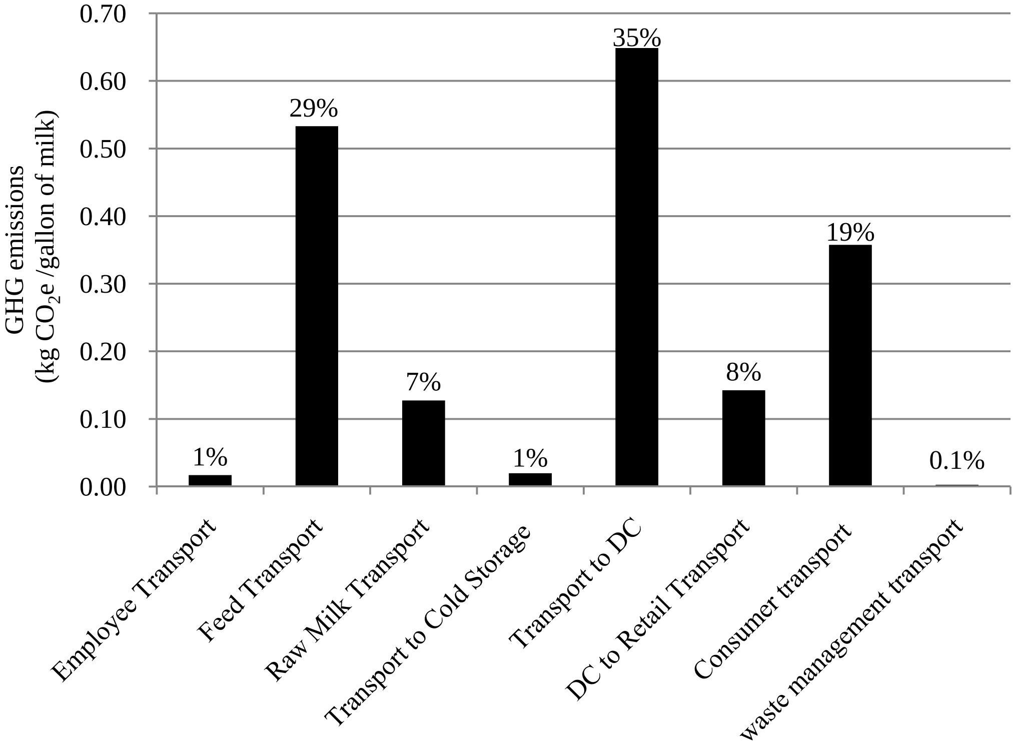

Figure 27: Break-down of transportation GHG emissions

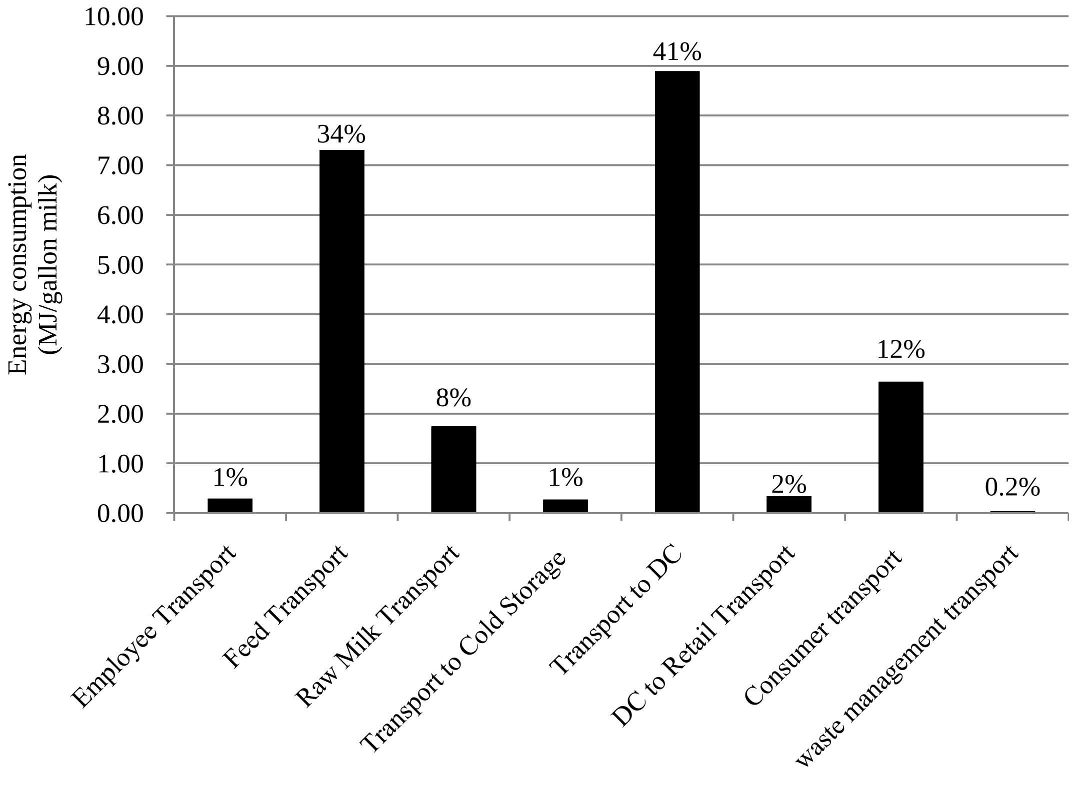

Figure 28: Break-down of transportation energy consumption

4.10. Refrigeration results

After the milk is packaged it is refrigerated until end of life. Overall, refrigeration contributes 15,400 tons of CO_2e to the total milk lifecycle in the time frame analyzed. This value is equivalent to approximatley 9% of all GHG emissions in the milk lifecycle. Milk is refrigerated in a warehouse style system at a cold storage facility and distribution centers, in a vertical closed door display case at the retail location, and in a 19 ft^3 refrigerator unit at the consumer's home. Consumer refrigeration accounts for the largest GHG emissions of all refrigerated processes, making up 51% of refrigeration GHG emissions (Figure 29). As mentioned in the methodology, if empty refrigeration space is not allocated to the milk, consumer refrigeration GHG values decrease substantially. Note that milk is also refrigerated in silos at the milk processing plant, but this study was not able to separate plant refrigeration from the total electricity usage at the milk plant. Refrigeration accounts for 268,000 GJ (6,100 gallons of gasoline equivalent LHV) of energy consumption or 17% of total energy consumed across the milk life cycle for the time frame of analysis. Again, consumer refreigeration accounts for the largest energy consumption for all refrigerated processes, 48%, with cold storage, distribution center, and retail refrigeration also consuming a significant amount of energy (Figure 30).

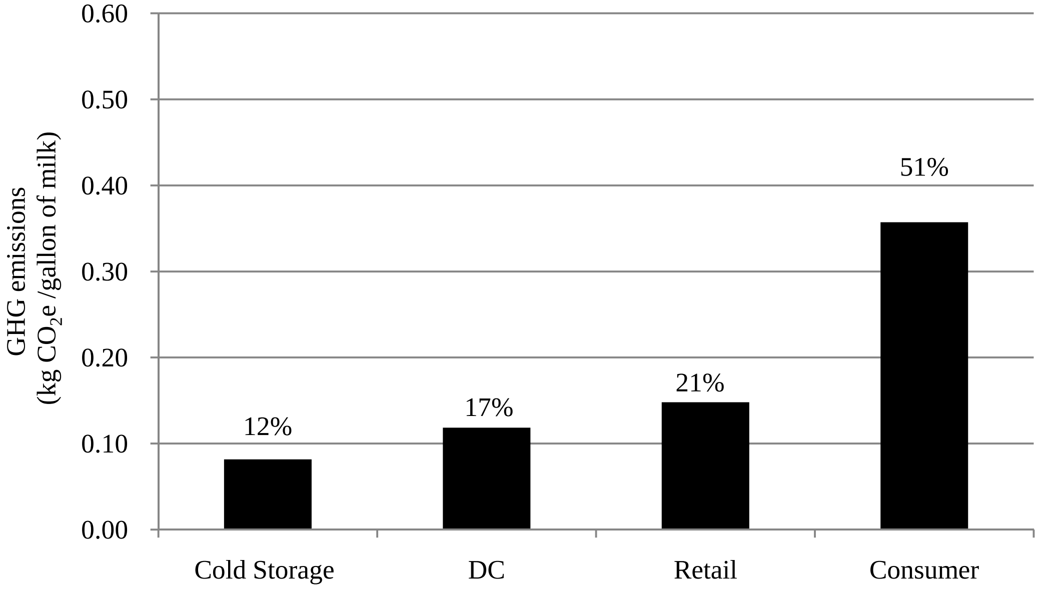

Figure 29: Break-down of refrigeration GHG emissions

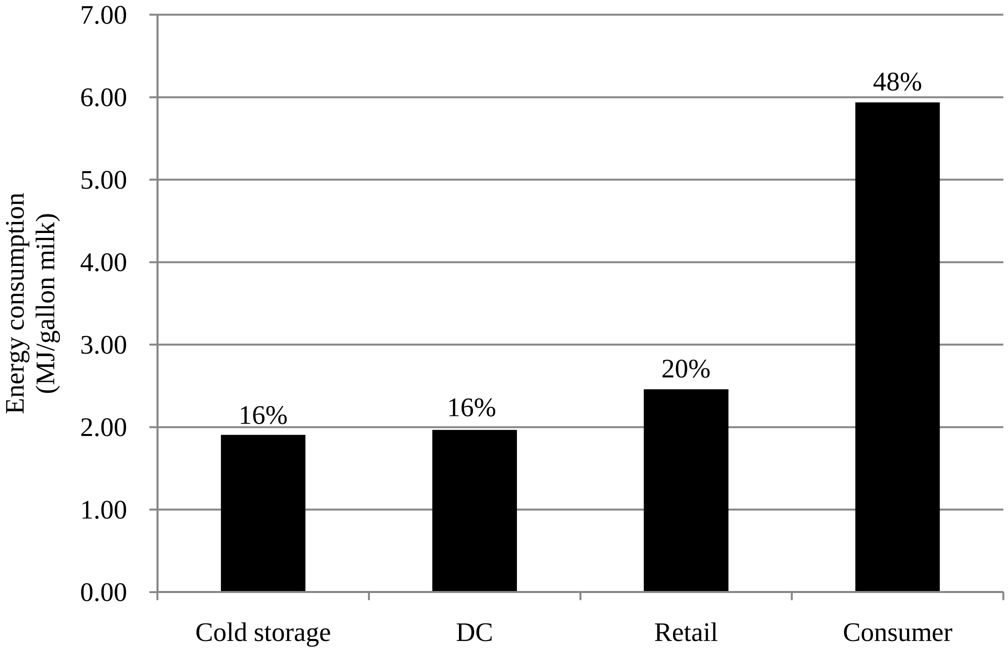

Figure 30: Break-down of refrigeration energy consumption

4.11. GHG component results

The three main GHGs considered in this analysis were carbon dioxide, methane, and nitrous oxide. As discussed above, carbon dioxide is generally considered the most significant anthropogenic GHG, but methane and nitrous oxide are important GHGs in the dairy system, both with significantly higher GWP than CO_2 (Table 4). Figure 31 shows the breakdown of total life cycle GHGs by type, and Figure 32 shows the breakdown of GHGs for each process in the milk life cycle. The largest GHG emissions from the milk life cycle are from CO_2, which contributes about 49% of all GHGs; however, CH_4 is also emitted in abundance during the milk life cycle, accounting for 45% of total GHG emissions (Figure 32). As can be seen in Figure 32, most CH_4 related emissions occur in the farm operations stage; whereas, CO_2 emissions occur throughout the entire milk life cycle, specifically in processes involving fossil fuel combustion such as transportation.

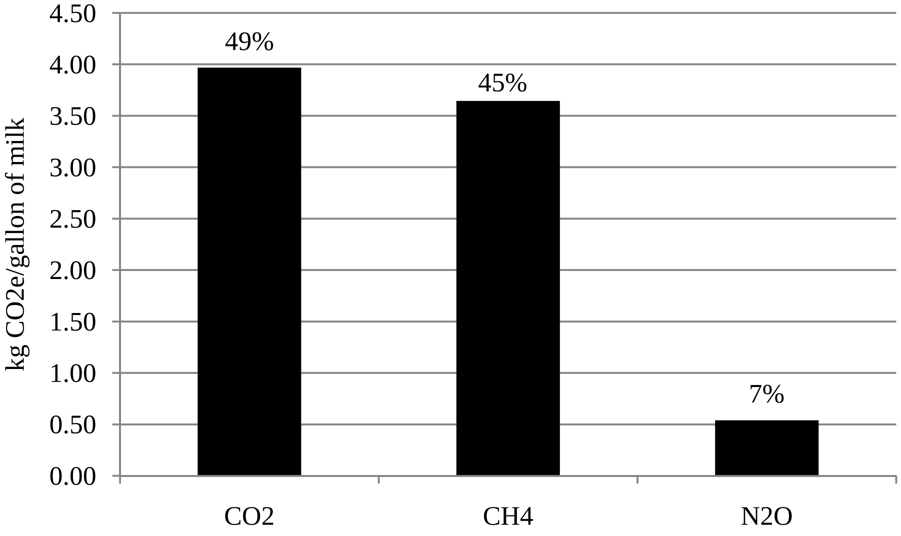

Figure 31: Contributions from each GHG considered in this study

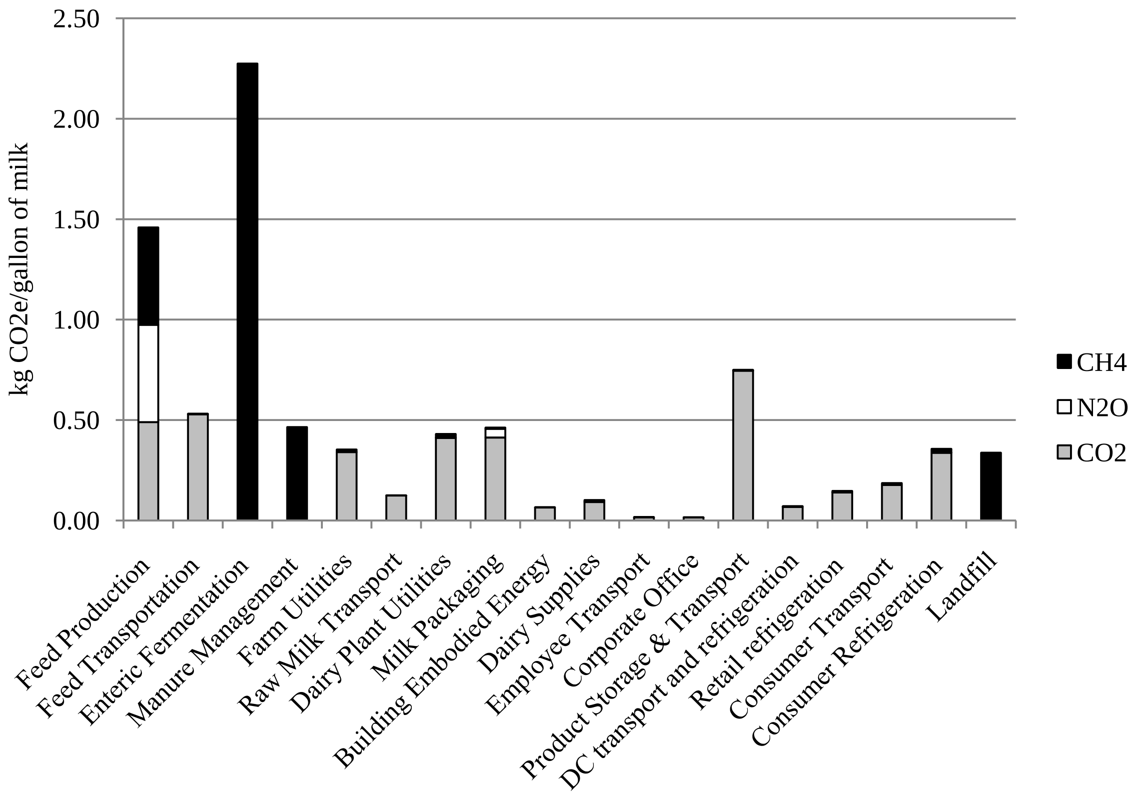

Figure 32: Break-down of GHG type by process across the entire milk life cycle

5. *Discussion*

5.1. Literature comparisons

Caution must be exercised in comparing life cycle results from this study with other results published in the literature. Differences in methods and model parameters can influence the comparison and lead to inaccurate conclusions. Because LCA is still under development and each country has its own agricultural techniques and climate there are significant differences in LCA results even among European countries. Table 9 shows the range of values from reported LCA studies of milk production and processing including this study.

Table 9: Comparison of literature reported LCA studies of milk production and processing up to farm gate and total life cycle

up to farm gate (per kg ECM)				
GHG (kg CO_2e/kg ECM)	energy (MJ/kg ECM)	country	Conventional or Organic	reference
1.1	-	US	C	Phetteplace (2001)[a]
0.81	1.4	Spain	C	Hospido (2003)
1.3 - 1.5	-	Ireland	C	Casey (2005)
1.0	3.6	Sweden	C	Cederberg (2000)
0.95	2.5	Sweden	O	Cederberg (2000)
0.89	3.7	Netherlands	C	de Boer (2003)
0.92	3.9	Netherlands	O	de Boer (2003)
1.3	2.7	Germany	C, intensive	Haas (2001)
1.3	1.2	Germany	O	Haas (2001)
1.4	5.0	Netherlands	C	Thomassen (2008)
1.5	3.1	Netherlands	O	Thomassen (2008)
-	5.3	Finland	C	Grönroos (2006)
-	2.8	Finland	O	Grönroos (2006)
1.35	5.19	US	O	this study
total life cycle (per gallon)				
(kg CO_2e/ gallon packaged milk)	MJ/ gallon packaged milk			
3.97	23.5	Spain	C	Hospido (2003)[b]
-	24.2	Finland	C	Grönroos (2006)
-	16.7	Finland	O	Grönroos (2006)
7.98	72.60	US	O	this study

[a] not reported as a LCA study
[b] does not include delivery of final packaged milk

5.2. Methodology of previous studies

As stated above, there is not a uniform method to conduct dairy LCAs. In fact, a literature review of past dairy LCA methodologies revealed that there is still an insufficient standardized methodology between studies to make accurate comparisons (de Boer, 2003). Differing methodologies remain the largest barrier to making a useful comparison between studies. Specific differences in methodologies include system boundaries, cow allocation, functional unit, software and datasets utilized, varying characterization methods, and number of farms and size of farms analyzed. Other differences include model parameters, such as different global warming potentials (GWP) applied to certain GHGs. Table 10 describes various past methodologies used for a sample of previously published dairy LCAs. One shortfall of past studies is that economic allocation has been utilized heavily for the selling of bull calves and culled cows. Economic allocation relies on volatile market prices of meat and milk. Other methodologies for cow allocation previously utilized are mass and biological allocation. Mass allocation is based on the ratio of milk produced to the ratio of meat produced, and biological allocation is based on the amount of energy required to produce milk in the form of feed versus the amount of energy to produce meat.

Table 10: A sample of methodologies utilized by previous dairy LCA studies (O = organic, C = conventional)

Author	Country	Cow Allocation	System Boundary	# and size of Farms
Casey (2005)	Ireland	Mass & Economic	Cradle to farm gate	Country estimate
Hospido (2003)	Spain	Biological	Cradle to farm gate and processing	2 farms:50 and 60 head
Cederburg (2000)	Sweden	Biological	At farm gate	2 farms (size = relatively large for Sweden)
Iepema & Pijnenburg (2001)	Netherlands	Economic	Cradle to farm gate	3 experimental farms, size not described
Haas (2001)	Germany	Not described	Cradle to farm gate	18 farms: ave. 23 head
Thomassen (2008)	Netherlands	Economic	Cradle to farm gate	10 C farms 11 O farms: 81 head ave. v. 71 head ave.

5.3. Feed production datasets

This analysis relied on available LCA datasets for feed production. No LCA datasets existed at the time of this study for U.S. organic feed production of feed types purchased by AOD. LCA datasets, specifically for agriculture, are more established for European systems than those in the U.S. U.S. datasets were only available for conventional corn, soybeans, and soybean meal. The base model considered in this analysis uses U.S. conventional datasets for corn, soybeans, and soybean meal, and Swiss (CH) organic datasets for all other organic feed types including alfalfa hay, flax meal, corn silage, grass silage, wheat midds, and millet hulls. The base model feed datasets were chosen to represent first geographic accuracy and second farming practices. To explore the effect of this assumption, two other feed scenarios were considered: all CH organic datasets and all CH conventional datasets. Overall, there is about a 6% increase in feed energy values and a 22% increase in feed GHG values when utilizing all CH conventional datasets rather than the base model datasets (Table 11). Some uncertainty also exists with the feed mass inputs into SimaPro. The SimaPro datasets for feed were based on dry matter weight. There could be some instances in which the weights used for feed could contain a significant amount of water weight. In such instances, emissions and energy estimates would be higher.

Table 11: Feed GHG and energy values when using different LCA datasets

	base model	CH Organic dataset	CH Conventional dataset
feed production (MJ)	212,766	190,766	373,000
percentage difference	X	-10.3%	75.3%
feed production (kg CO_2e)	32,200	32,400	42,400
percentage difference	X	0.621%	31.7%

5.4. Dynamic system analysis

The milk production system, specifically AOD, is a very dynamic system. The number of cows in milk at each farm changed dramatically throughout the timescale of this study. Other changes in the system could include changes in farming practices based on the climate (i.e. season). As stated in the methods, data was collected and modeled by month to represent the dairy system as a dynamic system, and take into account any seasonal changes. The number of cows in milk and the net herd differed throughout the year (Figure 34) due to the fact that the Dublin farm was sold in December 2007 and the Coldwater farm did not start milking operations until July 2007. It is difficult to determine the causation of GHG monthly changes from company or seasonal differences. Figure 33 shows the GHG emissions from all AOD farms by month. As can be seen, there does not appear to be a seasonal pattern of farm GHG emissions, although GHG emissions per ECM is slightly higher in the winter.

Changes in scale of individual farms influenced the GHG emissions per ECM. For instance, the overall GHG emissions per ECM at the Coldwater farm was high in comparison to the other farms. This result is likely due to the scaling up of the Coldwater farm over the time frame of analysis. As can be seen in Figure 40, the ratio of cows in milk to net herd increased over time, while the GHG per ECM decreased over time.

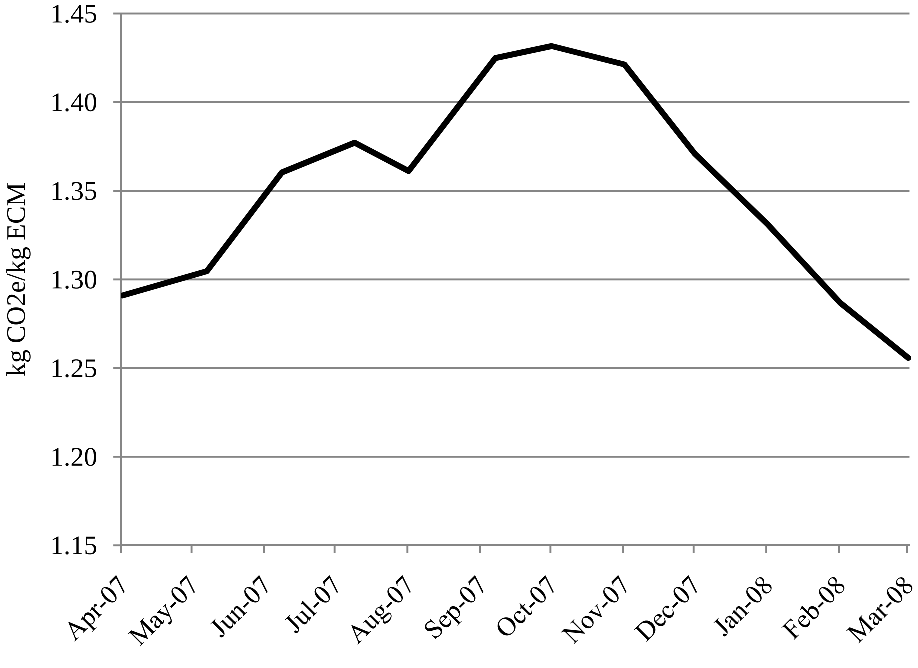

Figure 33: Monthly GHG emissions for all farms including feed per kg ECM

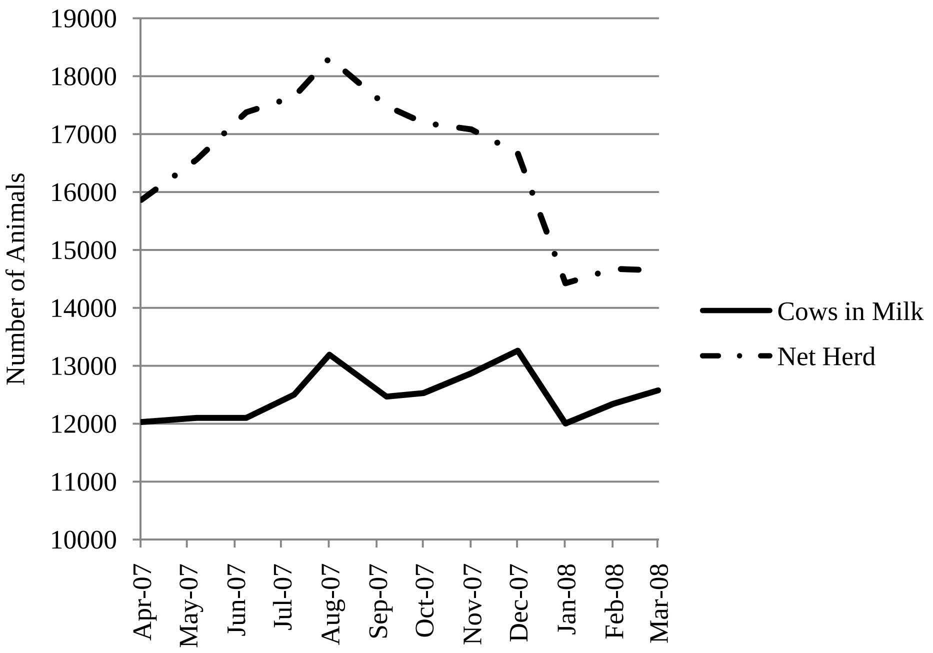

Figure 34: Net herd and cows in milk by month for all of the six AOD farms

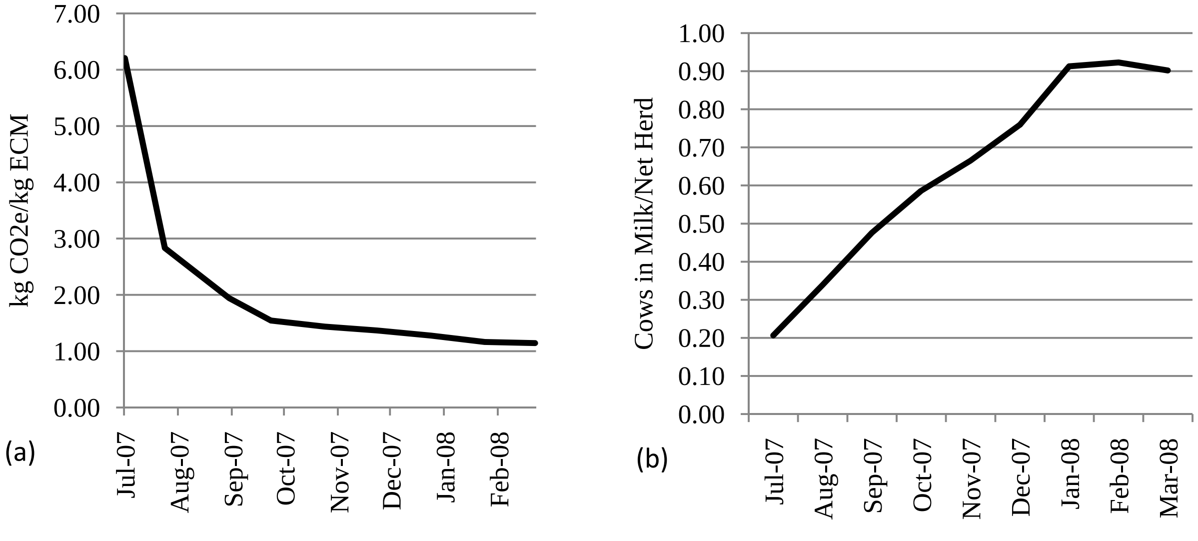

Figure 35: GHG emissions (kg CO2e/kg ECM) (a) Ratio of cows in milk to net herd (b) for Coldwater

5.5. Manure management comparison

Manure management has a large impact on GHG emissions within the dairy system, accounting for approximately 6% of total system CO_2e emissions, and 16% of the farm stage

CO_2e emissions. Manure management decisions, therefore, can have an important impact on GHG emissions. Table 12, based on the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, lists the methane conversion factor for different management systems. This variable indicates the degree to which the manure in each system produces methane. These values can, therefore, be looked to as a relative ranking for different manure management practices in terms of their effect on CO_2e emissions. Higher temperatures lead to higher emissions; the table lists relative contributions at three different annual average temperatures, <10°C, 14°C, and 17°C, which correspond to the Colorado farms, Coldwater, and Dipple/Dublin respectively.

Table 12: Methane conversion factors by manure management practice and temperature

	Annual Average Temperature		
Manure Management Practice	≤10°C	14°C	17°C
Daily Spread	0.1%	0.1%	0.5%
Compost (intensive windrow)	0.5%	0.5%	1.0%
Dry Lot	1.0%	1.0%	1.5%
Pasture	1.0%	1.0%	1.5%
Solid Storage	2.0%	2.0%	4.0%
Uncovered Anaerobic Lagoon	66.0%	73.0%	76.0%

Although CH_4 is the primary GHG resulting from manure management in terms of both raw emissions and contribution to CO_2e, N_2O emissions also result from manure decomposition in different systems. Each manure management practice listed in the table above, therefore, results in N_2O emissions not reflected in the methane conversion factor listed. The inclusion of these emissions, however, does not alter the relative rankings of the management systems in terms of CO_2e. Because of this fact, the percentages can be used as a relative CO_2e score for each system. The only manure management system whose ranking would change from considering N_2O emissions is composting, whose CO_2e ranking would approximately double, putting it on level footing with dry lot and pasture systems.

This analysis lends itself well to a case study at the High Plains farm investigating the effects of switching from solid storage to composting, which can also be used as animal bedding. By completely eliminating current solid storage management and replacing it with intensive windrow composting, yearly CO_2e emissions at the High Plains farm over the time period of the study would have been approximately 2.5% lower, or an avoidance of 450 tons CO_2e. This figure does not include any emissions from managed soils due to the addition of compost to the soil as an additive if it were used on farm. Additionally, if this compost displaced the use of all purchased bedding at High Plains, it would lead to another reduction of 84 tons CO_2e.

5.6. Allocation methodology analysis

In addition to the energy-based allocation methodology for end-of-life cows and bull calves that accounts for the feed burdens associated with the energy embodied in the co-products, an investigation into the expansion of this relationship to include the enteric fermentation emissions associated with the digestion of those same feed burdens was considered. Under the base case allocating only the feed burdens, each sold adult culled cow allocates 92.5 kg CO_2e away from the milk system and each sold bull calf allocates 19.3 kg CO_2e away from the milk system. The enteric fermentation emissions that those additional feedstuffs caused were determined according to the same on-farm diffuse GHG methodology described earlier in the report. This results in an additional 134.0 kg CO_2e allocated away from the milk system for each sold adult culled cow and an additional 27.9 kg CO_2e allocated away from the milk system for each sold bull calf. In terms of the overall system, using this expanded allocation methodology would result in an additional 880.0 tons CO_2e being allocated away from the milk system during the time frame of analysis. This total represents 0.5% of all CO_2e emissions resulting from the milk system during the time frame of analysis.

5.7. Abatement strategies

The nature of AOD's operations and the location of some of its farms present significant potential for the utilization of renewable energy systems. The employment of such systems could provide AOD with financially sound opportunities for greenhouse gas abatement. Furthermore, significant potential for abatement also exists in animal husbandry practices that seek to limit enteric fermentation. Five strategies for abatement were assessed:

- Displacement of on farm petro-diesel with a blend of 20% soybean methyl ester and 80% petro-diesel
- Use of an anaerobic digester to process animal waste and generate on farm electricity
- Potential for wind energy on AOD's farms
- Potential for photovoltaics on AOD's farms
- Manipulation techniques of animal diet to minimize emissions from enteric fermentation. (all diet changes would need to comply with the National Organic Program regulations for organic livestock production)

5.7.1. Biodiesel

An assessment was conducted looking at the abatement effects of displacing all of AOD's on farm petro-diesel usage with a B20 blend of soybean methyl ester. Fuel usage was taken from AOD records for the period examined in this study. An energy parity assumption was then made, meaning that the B20 blend assessed would be required to provide the same amount of energy as the petro-diesel did over this time period. Values of 118,000 BTUs per gallon of biodiesel and 130,500 BTUs per gallon of petro-diesel were used to compute the energy value of the B20 blend, around 98% of the petro-diesel value. This value was used to compute the amount of B20 biodiesel required for the provision of an amount of energy equivalent to that provided by the petro-diesel. This amount was then divided into fuel sub-categories of petro-diesel and biodiesel based on the blend percentage, 80% and 20% respectively. Life cycle emissions from the resulting amount of B20 biodiesel required to provide this amount of energy were then modeled using a “Diesel Equipment” dataset from Franklin Associates and a “Soybean Methyl Esther, production US, at service station” Ecoinvent dataset. It was assumed that there were no emissions from the combustion of biodiesel as it is carbon neutral. The biodiesel dataset was then compared to the life cycle emissions of petro-diesel from cradle-to-gate using a “Diesel Equipment” dataset from Franklin Associates and using the IPCC 2007 GWP 100a V. 1.03 methodology in SimaPro 7.0.

The results of this analysis reveal that substituting B20 soybean methyl ester for all petro-diesel used on farm would abate 310 tons CO_2e (0.16% of total emissions) and decrease fossil fuel usage by 20% annually. It is important to note that this analysis of biodiesel did not take into account any extreme land use changes that could take place from the expansion of bio-fuel crops and the resulting effects on the global carbon balance from such changes. Furthermore, the potential to displace feed with byproducts of bio-fuels production, such as soy hulls, and the resulting abatement that would occur from such displacement was not examined.

A rigorous financial assessment was not conducted for this strategy because of volatility in commodities markets that occurred over the period examined. In April of 2008, the end of the period examined in the study, the price of petro-diesel was $4.14/ gallon and the price of B20 blend biodiesel was $4.05/ gallon with petro-diesel energy equivalence. Thus, during this period a significant savings of around $25,000 would have been enjoyed by using a B20 blend instead of petro-diesel (EERE, 2008). This savings would have allowed AOD to save around $81/ton CO_2e abated. However, prices can change drastically and in the EERE report published on bio-fuel prices in January 2009 the price of petro-diesel was $2.44/gallon and the price of B20 blend biodiesel was $2.71/gallon with petro-diesel energy equivalence. Thus, there would be a loss from operating with B20 blend at these prices of around $75,000 relative to operation with petro-diesel which would mean that abatement would occur at a cost of around $242/ton CO_2e (EERE, 2009). These estimates highlight the extreme volatility that makes it difficult to predict the viability of bio-fuels as an abatement option at present.

Overall, it appears that bio-fuels could be a viable abatement option but it is recommended that AOD limit the usage of fuels that use corn or soy as a feedstock because of the land use and production ramifications such fuels have, like deforestation and the nutrient loading of hydrological systems resulting from fertilizer usage, and instead look to using fuels that have smaller land and input requirements, such as cellulosic ethanol. As such fuels are still in development, it may be best for AOD to delay transition to bio-fuels until more environmentally sound fuels can be developed in scale.

5.7.2. Wind energy

Significant potential exists for AOD to utilize wind power to provide electricity on its farms. For one, a few of AOD's farms are in ideal locations that have great inland wind energy potential. Secondly, the load for AOD's farms remains relatively constant throughout a 24 hour period, so wind energy could significantly displace grid energy used on farms and be financially viable without net-metering or other incentives based on feeding excess capacity into the grid. Thus, an assessment of wind energy was conducted using NREL's HOMER for four groups of

AOD facilities: High Plains/Ray-Glo, Coldwater, Dipple, and Platteville/Plant. Facilities were grouped based on proximity to one another, with grouped facilities being close enough to establish joint transmission from turbines and share electricity. In addition, CO_2e abatement created by displacing grid electricity with on-farm wind energy generation was measured using SimaPro.

Several assumptions were necessary in order to perform an assessment on wind energy potential for AOD's farms. For one, assumptions were made about the cost of wind turbines as well as what range of nameplate capacity should be examined for each farm. The assessment of a 330 kW Enercon turbine was deemed appropriate for High Plains/Ray-Glo, Coldwater, Dipple and Platteville/Plant. In addition, a 1.5 MW GE turbine was examined for Platteville/Plant because of the immense load of plant facilities. Sensitivities were conducted in HOMER looking at the quantity of turbines installed for each farm. Capital costs for the turbine were estimated at $1710/kW installed with sensitivity analyses conducted at 1.5 times this cost (Wiser & Bolinger, 2007). It was assumed that the life of the turbine was 25 years; however, sensitivities were conducted looking at shorter life spans and how they might affect the results. Replacement costs were estimated at half of the price of the turbine in the base year and subsequently annualized and embedded in the annual costs of operation. Operation costs were also included for all systems as 2% of installed capital costs on an annual basis. The interest rate used to examine the project was 6%. Wind speeds were taken from NOAA anemometers in Denver, CO for Platteville/Plant and High Plains/Ray-Glo, Amarillo, TX for Coldwater, and Dallas/Fort Worth, TX for Dipple. It was assumed that these anemometers were situated around 40m above ground. All turbines were also assumed to be situated around 40m above the ground as well; however sensitivities were conducted on turbine heights.

Electricity usage data was provided by AOD in the form of electricity bills. A full year of electricity usage, from April 2007 to March 2008, was used. Electricity costs, in terms of $/kWh, were taken from the EIA retail electricity data for industrial facilities on a state level. Per this data, it was assumed that AOD paid industrial retail rates of $0.059 per kWh in Colorado and $0.078 per kWh in Texas. In addition, sensitivities were conducted looking at how prices of $0.10 per kWh and $0.15 per kWh affected the results. Net-metering incentives were also examined with sell back rates of $0, $0.05, and $0.10 per kWh sold into the grid. Finally, greenhouse gas emissions from the grid were taken from a study done by Kim and Dale (2005) that looked at emissions on a region-by-region basis within NERC. The emissions within the ERCOT region that Dipple and Coldwater reside in were estimated to be 788 g CO_2e/kWh whereas the emissions within the WSCC region that the High Plains/Ray-Glo and Platteville/Plant groupings reside in were estimated to be 522 g CO_2e/kWh (Kim & Dale, 2005). SimaPro was then used to examine emissions from various scenarios, with the analysis method being the IPCC 2007 GWP 100a V. 1.03.

Results from the wind energy assessment reveal that wind is a relatively viable option for AOD. Without any subsidization, the installation of one 330 kW turbine was a cost effective abatement option for Coldwater and it became a cost effective abatement option for Dipple when a sensitivity analysis was conducted with electricity prices at $0.15/ kWh. With electricity prices at $0.15/kWh, Dipple and Coldwater would abate approximately 1,100 tons CO_2e annually (0.58% of total emissions) with a net present savings of $1.02 million. Thus, over the life of the project AOD would enjoy a savings of around $37.20/ ton CO_2e abated if it were to install turbines on its Coldwater and Dipple farms. Outside of these farms, wind energy remained unviable without subsidization. If AOD were to install 330 kW turbines on all of its farms it would abate around 1300 tons CO_2e annually (0.69% of total emissions). Assuming that AOD paid the EIA estimated rates on each farm, this scenario would cost \$1.31 million or approximately \$40/ ton CO_2e abated. Table 13, Table 14, Table 15, Table 16, Table 17, and Table 18 indicate the potential abatement for individual farms using wind energy.

Table 13: High Plains/Ray-Glo wind energy assessment (\$0.059/kWh)

Energy Mix	Initial Capital (\$)	Operating Cost (\$)	Total NPC (\$)	COE (\$/kWh)	Renewable %	Tons CO_2e abated annually
Grid Only	0	106,000	1,350,000	0.059	0	0
1 330 kW Turbine	564,000	108,000	1,930,000	0.084	0.10	120

Table 14: Platteville/plant wind energy assessment (\$0.059/kWh)

Energy Mix	Initial Capital (\$)	Operating Cost (\$)	Total NPC (\$)	COE (\$/kWh)	Renewable %	Tons CO_2e abated annually
Grid Only	0	489,000	6,250,000	0.059	0	0
1 330 kW Turbine	564,000	489,000	6,820,000	0.064	0.02	80
4 330 kW Turbine	2,260,000	491,000	8,530,000	0.081	0.09	370
1 1.5 MW Turbine	2,570,000	495,000	8,890,000	0.084	0.09	370
2 1.5 MW Turbine	5,130,000	509,000	11,600,000	0.11	0.17	700

Table 15: Coldwater wind energy assessment (\$0.078/kWh)

Energy Mix	Initial Capital (\$)	Operating Cost (\$)	Total NPC (\$)	COE (\$/kWh)	Renewable %	Tons CO_2e abated annually
Grid Only	0	195,000	2,490,000	0.078	0	0
1 330 kW Turbine	565,000	149,000	2,470,000	0.084	0.31	600

Table 16: Dipple wind energy assessment ($0.078/kWh)

Energy Mix	Initial Capital ($)	Operating Cost ($)	Total NPC ($)	COE ($/kWh)	Renewable %	Tons CO_2e abated annually
Grid Only	0	115,000	1,460,000	0.078	0	0
1 330 kW Turbine	564,000	83,800	1,640,000	0.087	0.43	498

Table 17: Dipple wind energy assessment ($0.15/kWh)

Energy Mix	Initial Capital ($)	Operating Cost ($)	Total NPC ($)	COE ($/kWh)	Renewable %	Tons CO_2e abated annually
Grid Only	0	220,000	2,820,000	0.15	0	0
1 330 kW Turbine	564,000	151,000	2,490,000	0.133	0.43	498

Table 18: Coldwater wind energy assessment ($0.15/kWh)

Energy Mix	Initial Capital ($)	Operating Cost ($)	Total NPC ($)	COE ($/kWh)	Renewable %	Tons CO_2e abated annually
Grid Only	0	374,000	4,780,000	0.15	0	0
1 330 kW Turbine	564,000	276,000	4,090,000	0.128	0.31	600

There are other viable options that exist for AOD to utilize wind energy on its farms that warrant consideration. For one, AOD could consider entering agreements with companies in which turbines would be installed on AOD farms provided AOD purchased from these turbines at mutually agreed upon rates. In this case, AOD would not have to worry about any upfront capital costs, but would have to consider whether or not rates from such a program would be viable. Secondly, AOD could consider leasing out some of its land to utilities for the installation of turbines. In this case, AOD would be compensated for its provision of land, but it may not be able to utilize any of the energy provided installed turbines. In this situation, AOD may not reduce its actual emissions, but it would contribute to the advancement of clean energy and abatement within the regional grid. It is worth noting that AOD purchased wind energy credits during the time period of the study, which also contributes to the advancement of clean energy and abatement within the regional grid, but was not incorporated into the model. All of these options would be dependent on AOD reaching an agreement with local utilities or other providers. Therefore, the financial viability of these options is subject to the terms of the contracts agreed upon. As the financial viability is unknown, both options merit further investigation by AOD as they have significant potential to improve the environmental sustainability of AOD's operations and mitigate emissions from the grid.

5.7.3. Photovoltaic energy

Photovoltaic energy potential was also examined for the four groupings above to see if it might be a viable option. As with wind, an energy assessment was conducted using NREL's HOMER and CO_2e abatement created by displacing grid electricity with on farm photovoltaic electricity generation was measured using SimaPro.

Several assumptions were necessary in order to perform an assessment on photovoltaic energy for AOD's farms. For one, assumptions were made about the cost of PV arrays as well as what range of nameplate capacity should be examined for each farm. The assessment of both a 100 kW and a 200 kW PV array was deemed appropriate for High Plains/Ray-Glo, Coldwater, Dipple and Platteville/Plant in order to establish an appropriate range for installed nameplate capacity. In addition, a 1 MW array was examined for Platteville/Plant because of its large load relative to other groupings. Capital costs for the PV array were estimated with a high of $7,000/kW installed, and sensitivity analyses were conducted at 0.67 and 0.33 times this cost

(United Nations Environment Programme-Energy Branch, 2008). The high end cost was a system cost, meaning it included costs for storage, inverters, and other component outside of the array itself. Though iterations were performed with the full range of potential upfront capital costs, it was more likely that a system AOD would install would fall in the mid to low end range of upfront capital costs. It was assumed that the life of the array was 30 years; however, sensitivities were conducted looking at shorter and longer life spans and how they might affect the results. Replacement costs for the array at the end of its life were estimated at half of the price of the array in the base year and subsequently annualized and embedded in the annual costs of operation. Operation costs were also included for all systems as 2% of installed capital costs on an annual basis. The interest rate used to examine the project was 6%. Solar energy data was imported into HOMER through NREL using the geographic coordinates of AOD facilities. Finally, the same assumptions made for the wind energy assessment in terms of the cost of electricity, the emissions from the grid, the sensitivities conducted for net-metering, and the assessment methodology used in SimaPro were made to complete the assessment for photovoltaic energy.

Results from our photovoltaic assessment provide some interesting insight into the viability of solar energy. With the high upfront capital cost of \$7,000/kW and rates of \$0.15/kWh, the net present cost of utilizing photovoltaics was significantly higher than that of using grid over the time period examined. The range of abatement from using PV was 430 tons CO_2e annually with 100 kW arrays (0.23% of total emissions) installed on all farms to 845 tons CO_2e annually with 200 kW arrays installed on all farms (0.45% of total emissions). Net present costs beyond those of just purchasing from the grid for achieving this annual abatement were \$2.19 million for installation of 100 kW arrays and \$4.42 million for installation of 200 kW arrays on all farms. Thus, costs per ton of CO_2e abated over the life of the project were quite large at \$170/ ton CO_2e and \$174/ ton CO_2e respectively for the 100 and 200 kW arrays.

The low upfront capital cost sensitivity of around \$2,310/kW yielded promising results when rates were \$0.15/kWh. Under these assumptions, it was viable for all farms to install at least 200 kW capacity, and it was viable for Platteville/Plant to install 1,000 kW of capacity. At these levels of capacity significant abatement of around 1,450 tons CO_2e annually (0.77% of total emissions) was achieved. The net present savings of installation relative to purchasing from the grid was \$0.353 million. This represents a total savings of around \$8/ ton CO_2e during the life of the project. In sum, with lower upfront capital costs it becomes viable for AOD to install photovoltaic arrays on all of its farms. As there is significant promise in photovoltaics, AOD should familiarize itself with incentives that may bring down the cost of photovoltaic energy on a state and federal level. For example, Xcel Energy has offered rebates of up to \$200,000 for onsite solar generation at certain facilities in Colorado in exchange for renewable energy credits (XCEL Energy, 2008). Other utilities have offered similar rebates in both Colorado and Texas, and low interest financing options exist for solar projects in both states. Such incentives may make the use of photovoltaics a financially viable option or further improve their viability. Thus, significant potential may exist for abatement through the use of photovoltaic energy at a net savings to AOD.

5.7.4. Anaerobic digester

The large amount of animal waste produced by AOD's farms presents a potentially valuable feedstock for energy creation via anaerobic digestion. Anaerobic digestion is a process in which bacteria break down biodegradable material in the absence of oxygen and produce biogas (primarily methane). There are essentially three steps to this decomposition; hydrolysis, where organic matter is broken down into simple soluble organics; acidogenesis, where these simple soluble organics are then broken down by acidogens into acetic acid and H_2; and, methanogenesis, where methanogens convert acetic acid into water, carbon dioxide and methane. The resulting methane can then be burned to power a turbine, thereby displacing electricity from the grid, or it can directly displace on farm natural gas usage. As such, anaerobic digestion could present a potentially viable abatement option and should be investigated.

Fortunately, during the time that this study was being conducted, a joint study between ActNeutral LLC, AOD, Colorado State University, and Landmark Engineering (2008) was underway looking at the feasibility of an anaerobic digester for the Platteville farm. There are several different types of digesters, each designed for usage in different environments. This study concluded that because of the nature of the organic waste and waste management system on the Platteville farm, a plug-flow digester was the most appropriate as it is a low-cost, low-maintenance system that can process a variety of substrates. Depending on the substrate mix, the digester could produce anywhere between 1,141 and 5,506 MWh of energy per year, all of this displacing electricity that would have been drawn from the grid. Using WSCC region greenhouse gas emissions provided by Kim and Dale (2005), such a digester installed at Platteville would abate anywhere between 588 and 2,840 tons CO_2e annually (0.31% to 1.51% of total emissions). Despite the energy savings and greenhouse gas abatement, an aerobic digester is not a financially viable option for the Platteville farm at this time as the study concluded that a plug-flow digester would have an NPV of -\$1.3 million and an IRR of -13% (ActNeutral LLC; Colorado State University, 2008). Extrapolating these pilot results out to AOD's other farms, it does not appear that an anaerobic digester is a viable option at this time without significant subsidization or a price on carbon.

5.7.5. Animal husbandry

As this study suggests, the greenhouse gas emissions from enteric fermentation are a major contributor to the carbon footprint of dairy operations. Finding cost-effective ways to mitigate the emissions from enteric fermentation could have an enormous impact on AOD's overall emissions levels. In addition to greenhouse gas abatement potential, the mitigation of enteric fermentation can also drastically improve milk production in dairy cattle per feed energy unit input. Estimates indicate that a 25% reduction in methane emissions from enteric fermentation in a dairy cow could increase milk yield by 1 L/d (Beauchemin, McGinn, Martinez, & McAllister, 2007). Several studies have been conducted looking at the effects diet manipulation or various dietary supplements have on methane emissions from enteric fermentation. A study by Beauchemin et al. looking at tannin extract as a supplement found that the introduction of tannin as 2.5% of the daily dry matter intake of cattle could reduce methane emissions by up to 12%, however the resulting effects of tannin introduction on the digestibility of crude protein (CP) in the animal diet made tannin extract an ineffective abatement option (Beauchemin, McGinn, Martinez, & McAllister, 2007). A study by Grainger et al. found that increasing dietary oils could mitigate emissions from enteric fermentation, with a 1% increase in dietary oils creating a 6% decrease in methane emissions. As part of this study, whole cottonseed was introduced into the animal diet and methane abatement of around 12% was observed. In addition to methane abatement, a 15% increase in milk yield was observed along with a 19% increase in milk fat and a 16% increase in milk protein (Grainger, Clarke, Beauchemin, McGinn, & Eckard, 2008).

There appear to be viable options that AOD might consider exploring to mitigate diffuse emissions from enteric fermentation on their farms. However, this study cannot make a claim as to what type of strategy should be implemented by AOD for several reasons. For one, the basal diet examined in the Grainger et al. study differs from the diet of AOD's cows. The magnitude of abatement from employing such a strategy is unknown and would have to be investigated by AOD. Secondly, there are limitations to the amount of certain types of organic feed, like whole cottonseed, AOD can purchase, and the cost of certain organic feeds may make their utilization financially infeasible in the absence of a price on carbon. Finally, because of organic standards AOD may not be able to employ future cost-effective measures developed to mitigate emissions from enteric fermentation, such as the administration or antibiotics like rumensin or chemicals like bromoethanesulphonate. That being said, it is recommended that AOD make a concentrated effort to devise ways in which it can mitigate emissions from enteric fermentation as this approach harbors enormous potential for cost-effective abatement of greenhouse gases. An effective abatement strategy will have to be appropriately tailored to the market and structural conditions of AOD's dairies and their surrounding regions and will, therefore, require further research and effort on AOD's part. It is recommended that AOD partner with animal scientists at Colorado State University to examine the potential for methane abatement through animal husbandry measures. This approach will allow AOD to examine ways in which it can cost effectively abate given the regional conditions and organic standards it must conform to.

5.8. Next steps in research

The study reported here has continued into a second phase, also conducted by researchers at the Center for Sustainable Systems. The second phase will build on the research presented in this report by defining and evaluating additional environmental sustainability indicators across the life cycle. In addition, the next phase of this study will contextualize these environmental indicators in a sustainability framework that also includes social and economic aspects, as a guide for further development of AOD's sustainability assessment and reporting

The environmental indicators to define and evaluate include:

- Water use: quantification of water usage across the product life cycle. In addition, indications of water stress and water scarcity (i.e., concern with the source of the water and its relative availability) will also be incorporated.
- Nutrient use: quantification of nutrient usage and usage efficiency across the product life cycle. Nutrient management is an important component of sustainable agriculture practices. These indicators will seek to identify the flow of nutrients across major system components (e.g., at the farm level) and assess use efficiency. Nitrogen flows will be the primary focus but analysis may also be expanded to phosphorus and other relevant nutrients.
- Solid waste generation: quantification of solid waste generated across the product life cycle. This indicator will involve a more careful look at manure management practices, and will also quantify waste generation (paper towel, scrap, etc.) at the various life cycle stages.

It is commonly recognized that sustainability must have a social and economic component. A growing body of literature addresses this three-pillared approach to sustainability and numerous frameworks and indicator selection criteria have been proposed. The second phase of this study will review this body of literature and formulate a sustainability framework suitable for AOD. Such a framework will not only serve as a reminder of other sustainability components but will also provide the groundwork for future assessment.

6. Conclusion

The overall life cycle GHG emissions per gallon final liquid packaged milk were 7.98 kg CO_2e. The overall life cycle GHG emissions per kg ECM at farm gate were 1.35 kg CO_2e, Enteric fermentation was the largest source of GHG emissions. Feed production and product storage and transport also made significant contributions to life cycle GHG emissions. On a farm basis, Dipple was found to have the greatest GHG emissions per kg ECM which can be attributed to the manure management system utilized by the farm.

There were several other significant contributors to emissions throughout the milk life cycle. The greatest contributors to the milk processing stage emissions were the dairy plant utilities and milk packaging. Transport to distribution centers and the transportation of feed were the greatest sources of emissions from transportation. Finally, consumer refrigeration and the landfill disposal of packaging were responsible for the greatest amount of emissions when looking at the consumer to end of life stage.

The overall life cycle energy consumption per gallon of final liquid packaged milk was found to be 72.6 MJ (1.65 gallons of gasoline equivalent LHV). The overall life cycle energy consumption at the farm gate per kg ECM was 5.19 MJ (0.12 gallons of gasoline equivalent LHV). The greatest sources of energy consumption for final liquid packaged milk in descending order were: product storage and transportation, product packaging, feed production, and dairy plant utilities.

6.1. Methodology issues and future refinements

The key constraint to this study was the lack of primary data availability for organic feed production in the US. Geographic coverage and farming technique, as it is currently represented in the model, is not precise to this study. The robustness of this study would be improved in the future with increased LCA data availability for organic US cropping systems. This study also relied on literature values for all processes past the distribution center in the milk product life cycle. Collection of primary data for retail and consumer processes would increase the strength of this study. For all stages other than the feed production stage and the consumer and end of life stage, availability of primary data was not an issue.

The model used for manure management systems in this study only includes diffuse emissions associated with those systems, which may be an oversimplification. For example, although solid manure management systems emit far fewer diffuse emissions than liquid manure management systems, they may require a heavier emissions burden in terms of farm operations including tractor and fuel use as well as transportation. Future refinements should investigate the portions of on farm fuel use associated with solid manure management systems as well as the transportation of that solid manure off farm. Incorporating those associated emissions together with diffuse emissions would provide a more complete normalized comparison across manure management systems.

Methodological choices concerning co-product allocation can also influence the results in a potentially significant manner. The most interesting and difficult co-product allocations performed in this study were for end of life cows and bull calves. Rather than using economic allocation, a more causal energy based allocation was performed. The difficulty lies in parsing out exactly what portion of farm energy use and emissions are the result of milk production versus the production of adult culled cows or bull calves. Allocations with different assumptions and boundaries could be undertaken in order to gauge sensitivity of the system to these methods.

6.2. Recommendations

Several key recommendations that may help AOD improve the GHG and energy performance of its operations were identified in this study. These recommendations are as follows:

- Improve the manure management system at the Dipple Farm. Currently, Dipple has a management system that relies heavily on flushing waste into anaerobic lagoons. These lagoons are significant contributors to global warming because they produce a disproportionately large amount of methane as compared to the dry manure management systems utilized on other AOD farms. It is recommended that AOD either transition to a dry manure management system or flare the methane from the lagoons to reduce emissions at Dipple.

- Examine ways in which diffuse emissions from enteric fermentation can be abated. Enteric fermentation is the greatest contributor to AOD's life cycle emissions. AOD's must find ways to abate emissions from enteric fermentation as this option harbors enormous potential for cost effective abatement of GHG emissions. It is, therefore, recommended that AOD's partner with animal scientists at Colorado State University, whom they have worked with on previous projects, in an attempt to devise methods to mitigate enteric fermentation through the manipulation of animal diet or other practices.

- Examine ways in which alternative energy can be utilized by AOD's facilities. Significant potential exists for the employment of clean, alternative energy technologies on AOD's farms that can displace energy from the grid. In particular, wind turbines present a cost effective option for AOD on its farms in Texas, and photovoltaics may be viable on all AOD's farms. It is also important that AOD be aware of developing incentives on a state, regional, and federal level that may make these options, as well as others, cost effective.

- Perform energy audits and make energy efficiency improvements at older AOD facilities. The majority of AOD's facilities are relatively new and use efficient equipment. There are, however, some facilities that may be in need of efficiency improvements. It is, therefore, recommended that AOD perform audits to examine the efficiency of older facilities, such as those on the Dipple farm, in order to uncover inefficient areas and subsequently improve them.

6.3. Future research

As stated in next steps in research, a second Center for Sustainable Systems study funded by the AOD Foundation is currently underway looking at additional sustainability indicators, including social and economic indicators, in an effort to develop a comprehensive sustainability framework that AOD and other dairies can use to improve the sustainability of its operations. AOD intends to share this study with the broader dairy community to improve the overall sustainability of the dairy industry. This model, along with other data collected, will be used to analyze various scenarios for the production and distribution of AOD’s product in an attempt to optimize economic, social, and environmental performance.

In addition to this, it may be valuable for AOD to set up an ongoing GHG inventory system that it can utilize to keep track of its performance. Establishing such a system will allow AOD to highlight troublesome areas, and areas of improvement, in its operations and ensure that it is growing sustainably. Such a system could be set up within AOD’s operations, or it could be jointly implemented by AOD and CSS, with AOD providing data and CSS analyzing and reporting emissions.

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Appendix A – Detailed Results

Data Category	**GHG Totals (Tons CO2e)**	**GHG Totals (kg CO2e)**	**Percent of Total Life Cycle**
Bedding	413	375,829	0.22%
Farm Embodied Energy	1,001	910,072	0.53%
Enteric Fermentation	47,865	43,513,664	25.41%
Feed Production	32,200	29,272,779	17.09%
Managed Soils	14	12,849	0.01%
Manure Management	11,156	10,142,193	5.92%
Pasture Planting/Cutting	230	209,423	0.12%
Farm Purchased Items	2,342	2,129,540	1.24%
Farm Employee Transportation	264	239,915	0.14%
Feed Transportation	12,756	11,596,777	6.77%
Farm Diesel & Gasoline	2,990	2,718,022	1.59%
Farm Electricity	4,260	3,872,587	2.26%
Farm Municipal Water	80	72,637	0.04%
Farm Natural Gas & Propane	1,176	1,069,287	0.62%
Raw Milk Transportation To Plant	3,034	2,757,819	1.61%
Cold Storage	1,957	1,779,275	1.04%
Management Office Embodied Energy	0	417	0.00%
Management Employee Travel	280	254,525	0.15%
Management Purchased Items	11	10,064	0.01%
Management Office Electricity	55	49,581	0.03%
Management Office Municipal Water	0	54	0.00%
Management Office Natural Gas	25	22,830	0.01%
Powder Transportation	205	186,507	0.11%
Powder Packaging Materials	4	3,491	0.00%
Powder Production	205	186,534	0.11%
Plant Embodied Energy	248	225,793	0.13%
Plant Employee Transportation	140	127,241	0.07%
Gallon Packaging Materials	430	391,311	0.23%
Half Gallon Packaging Energy	1,023	930,440	0.54%
Half Gallon Packaging Materials	9,656	8,778,461	5.13%
Plant Purchased Items	113	102,407	0.06%
Plant Electricity	4,251	3,864,165	2.26%
Plant Municipal Water	26	23,909	0.01%
Plant Natural Gas	5,546	5,041,597	2.94%
Plant Wastewater Treatment	328	298,075	0.17%
Transportation To Cold Storage	474	430,691	0.25%
Transportation To Distribution Center	15,534	14,121,994	8.25%
Consumer Refrigeration	8,569	7,790,153	4.55%
Consumer Transport	4,473	4,066,375	2.37%
DC Refrigeration	2,839	2,581,263	1.51%
DC To Retail Transport S	572	519,708	0.30%
DC To Retail Transport Refrigeration	20	18,076	0.01%
Landfill	8,021	7,291,589	4.26%

Retail Refrigeration	3,549	3,226,583	1.88%
Waste Management Transport	60	54,391	0.03%
Total	**188,398**	**171,270,893**	

Data Category	**Energy Totals (GJ)**	**Percent of Total Life Cycle**
Bedding	3,563	0.23%
Farm Embodied Energy	16,622	1.05%
Feed Production	212,767	13.44%
Pasture Operations	3,981	0.25%
Farm Purchased Items	37,779	2.39%
Farm Employee Transportation	4,116	0.26%
Feed Transportation	158,974	10.04%
Farm Diesel & Gasoline	38,063	2.40%
Farm Electricity	93,068	5.88%
Farm Municipal Water	2,590	0.16%
Farm Natural Gas & Propane	18,072	1.14%
Raw Milk Transportation To Plant	37,823	2.39%
Cold Storage	41,570	2.63%
Management Office Embodied Energy	6	0.00%
Management Employee Travel	4,360	0.28%
Management Purchased Items	138	0.01%
Management Office Electricity	1,158	0.07%
Management Office Municipal Water	2	0.00%
Management Office Natural Gas	414	0.03%
Powder Transportation	2,558	0.16%
Powder Packaging Materials	179	0.01%
Powder Production	3,386	0.21%
Plant Embodied Energy	3,388	0.21%
Plant Employee Transportation	2,205	0.14%
Gallon Packaging Materials	7,059	0.45%
Half Gallon Packaging Energy	18,166	1.15%
Half Gallon Packaging Materials	195,305	12.34%
Plant Purchased Items	1,943	0.12%
Plant Electricity	90,279	5.70%
Plant Municipal Water	853	0.05%
Plant Natural Gas	91,515	5.78%
Transportation To Cold Storage	5,904	0.37%
Transportation To Distribution Center	193,634	12.23%
DC Refrigeration	42,898	2.71%
DC To Retail Transport	7,128	0.45%
DC To Retail Transport Refrigeration	246	0.02%
Retail Refrigeration	53,623	3.39%
Consumer Transport	57,606	3.64%
Consumer Refrigeration	129,465	8.18%
Waste Management Transport	806	0.05%
Total	**1,583,215**	

Appendix B - Manure Management System Description [2006 IPCC Guidelines for National Greenhouse Gas Inventories]

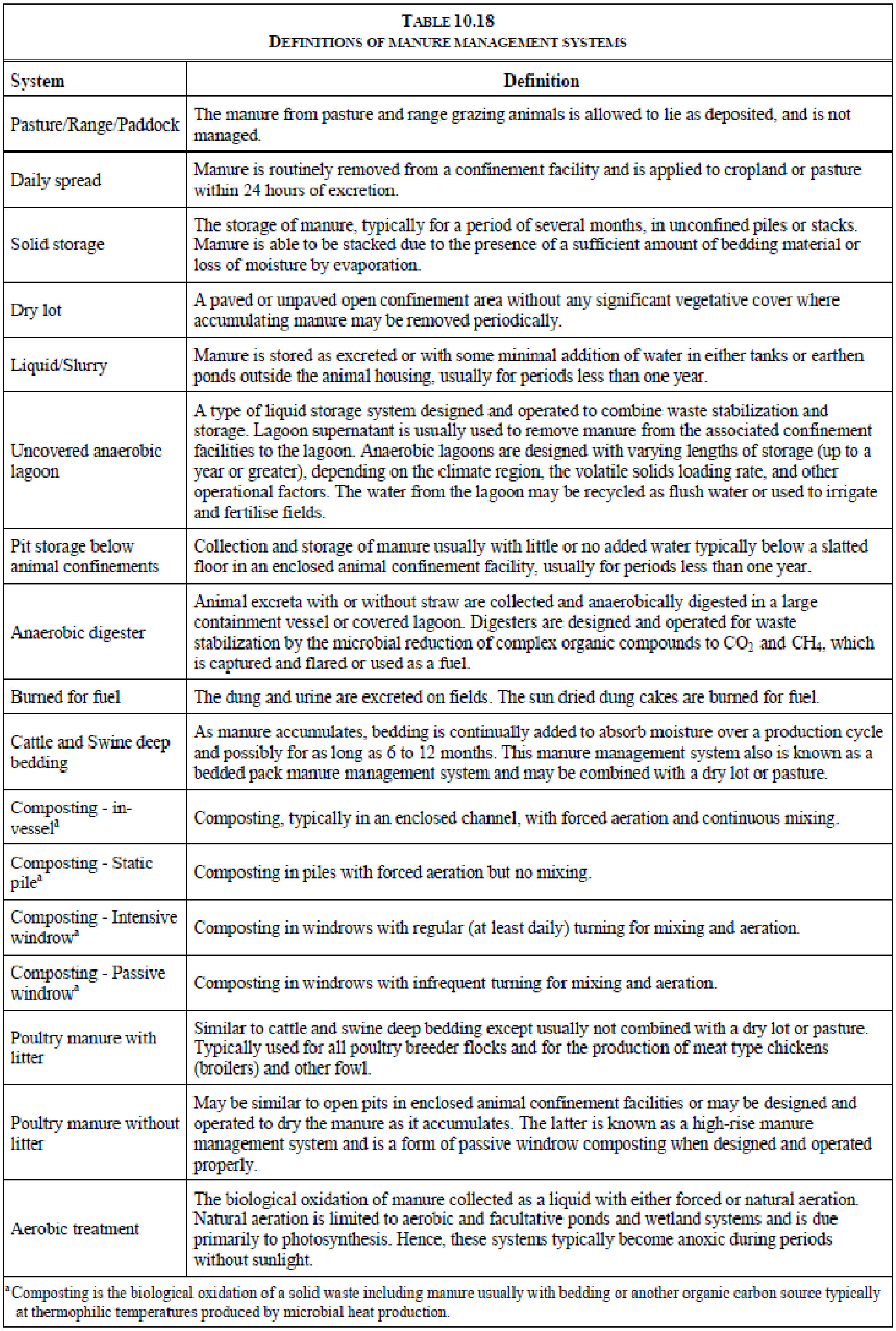

TABLE 10.18
DEFINITIONS OF MANURE MANAGEMENT SYSTEMS

System	Definition
Pasture/Range/Paddock	The manure from pasture and range grazing animals is allowed to lie as deposited, and is not managed.
Daily spread	Manure is routinely removed from a confinement facility and is applied to cropland or pasture within 24 hours of excretion.
Solid storage	The storage of manure, typically for a period of several months, in unconfined piles or stacks. Manure is able to be stacked due to the presence of a sufficient amount of bedding material or loss of moisture by evaporation.
Dry lot	A paved or unpaved open confinement area without any significant vegetative cover where accumulating manure may be removed periodically.
Liquid/Slurry	Manure is stored as excreted or with some minimal addition of water in either tanks or earthen ponds outside the animal housing, usually for periods less than one year.
Uncovered anaerobic lagoon	A type of liquid storage system designed and operated to combine waste stabilization and storage. Lagoon supernatant is usually used to remove manure from the associated confinement facilities to the lagoon. Anaerobic lagoons are designed with varying lengths of storage (up to a year or greater), depending on the climate region, the volatile solids loading rate, and other operational factors. The water from the lagoon may be recycled as flush water or used to irrigate and fertilise fields.
Pit storage below animal confinements	Collection and storage of manure usually with little or no added water typically below a slatted floor in an enclosed animal confinement facility, usually for periods less than one year.
Anaerobic digester	Animal excreta with or without straw are collected and anaerobically digested in a large containment vessel or covered lagoon. Digesters are designed and operated for waste stabilization by the microbial reduction of complex organic compounds to CO_2 and CH_4, which is captured and flared or used as a fuel.
Burned for fuel	The dung and urine are excreted on fields. The sun dried dung cakes are burned for fuel.
Cattle and Swine deep bedding	As manure accumulates, bedding is continually added to absorb moisture over a production cycle and possibly for as long as 6 to 12 months. This manure management system also is known as a bedded pack manure management system and may be combined with a dry lot or pasture.
Composting - in-vessel[a]	Composting, typically in an enclosed channel, with forced aeration and continuous mixing.
Composting - Static pile[a]	Composting in piles with forced aeration but no mixing.
Composting - Intensive windrow[a]	Composting in windrows with regular (at least daily) turning for mixing and aeration.
Composting - Passive windrow[a]	Composting in windrows with infrequent turning for mixing and aeration.
Poultry manure with litter	Similar to cattle and swine deep bedding except usually not combined with a dry lot or pasture. Typically used for all poultry breeder flocks and for the production of meat type chickens (broilers) and other fowl.
Poultry manure without litter	May be similar to open pits in enclosed animal confinement facilities or may be designed and operated to dry the manure as it accumulates. The latter is known as a high-rise manure management system and is a form of passive windrow composting when designed and operated properly.
Aerobic treatment	The biological oxidation of manure collected as a liquid with either forced or natural aeration. Natural aeration is limited to aerobic and facultative ponds and wetland systems and is due primarily to photosynthesis. Hence, these systems typically become anoxic during periods without sunlight.

[a] Composting is the biological oxidation of a solid waste including manure usually with bedding or another organic carbon source typically at thermophilic temperatures produced by microbial heat production.

Appendix C: Net Energy Requirement for Pregnancy Equation [National Research Council 2001]

NE_L (Mcal/d) = [(.00318 X D - .0352) X (CBW/45)] / .218

where D = day of gestation from 190 to 279, and CBW = calf birth weight in kg