Greenhouse Gas Emission Reduction Associated with Livestock Waste Management Systems: A Case Study for the Langerwerf Dairy Waste Management System

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Abstract

By using anaerobic digestion (AD) technology, a 400-cow dairy farm near Durham, California has reduced greenhouse gas (GHG) emissions and global warming potential (GWP) by approximately four-fifths (79%). The dairy-waste management system at the farm incorporates an AD system that produces biogas, electricity and heat through the use of a combined heat and power unit. The analysis compared the GHG emissions and GWP associated with the AD system and a reference system without anaerobic digestion, over a 50-year life cycle. The analysis considered the emissions of carbon dioxide, methane and nitrous oxide associated with installing, operating and ultimately closing down each waste-management system. The analysis indicates that by avoiding decomposition of the manure in open storage ponds and eliminating combustion of fossil fuels to heat water, the anaerobic system very significantly reduces GHG emissions. On the basis of this study it is recommended that livestock waste management systems should include AD systems as a way to reduce GHG emissions and global warming.

Background

In the United States an estimated 376,000 livestock operations produce approximately 58 million metric tons of manure annually. Over the past two decades, these operations have become increasingly specialized, and production methods more intensive. The associated increase in air and water contamination has led the U.S. Environmental Protection Agency (U.S. EPA) and the U.S. Department of Agriculture (U.S.D.A) to enact permit requirements and effluent guidelines for nearly 40,000 of the largest operations. One approach to meeting the more stringent requirements being adopted by the large operations is installation of anaerobic digestion (AD) systems into the waste management systems. The AD systems convert the livestock waste into biogas which in turn can be used to meet local energy demands. The livestock waste residue following digestion is a stabilized material that can be separated into a liquid and solids fraction. The liquid fraction is a good source of plant nutrients while the solid fraction is a good soil conditioner.

Impact of livestock waste management practices on the environment

Livestock waste management practices produce significant amounts of greenhouse gases. Greenhouse gases (GHG) are gases in the atmosphere that trap energy from the sun and energy produced by activities here on earth. Naturally occurring GHGs include water vapor, ozone, carbon dioxide, methane and nitrous oxide. While these gases are what make life possible, a serious concern today is the enhanced effect on the climate system of increased levels of the gases in the atmosphere due mainly to human actions. GHGs whose increase is directly associated with human activities are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O).

Carbon dioxide is released to the atmosphere when solid waste, fossil fuels (petroleum, natural gas, and coal), and/or wood and wooden products are burned. Carbon dioxide is also released in non-energy-related manufacturing processes and in decomposition of organic matter. Methane is emitted during the production and transport of fossil fuels. Methane emissions also result from the decomposition of organic wastes in an oxygen-deprived environment. Nitrous oxide is chiefly emitted during agricultural and industrial activities. Livestock waste management practices can impact GHG emissions by its impacts on energy consumption, methane and carbon dioxide generation, carbon sequestration, and non-energy-related manufacturing emissions. This paper describes the results obtained from a case study that examined the impacts of anaerobic digestion of dairy manure on GHG emissions from a life-cycle perspective.

The objectives of the study were as follows:

1.   To determine the greenhouse gas emissions associated with the installation, operation, and decommissioning of AD systems for energy production and dairy waste management (DWM).

2.   To estimate the quantity of GHG emissions avoided through the use of AD systems in DWM systems operation.

3.   To compare the quantity of GHG emissions from DWM systems with and without AD systems.

The life cycle GHG case study and Reference System

A 50-year full life cycle analysis (LCA) of GHG emissions was conducted on the AD System operated by the Langerwerf family of Durham, California. The GHG emissions from the AD System were compared with those that would have been released without the use of that system on the dairy farm. The livestock waste management system prior to installation of the AD System was considered the *Reference System*. The Langerwerf family currently operates a 400-cow dairy farm with a plug-flow AD System that produces electricity and hot water through the use of a biogas engine-generator equipped with a heat recovery unit. The effluent from the digester is separated into solids and liquid fractions. The solids are used as bedding in freestalls and calf barns and as a soil conditioner. The wastewater is applied as fertilizer to a field of corn. The hot water from the engine is used for maintaining a temperature of 95 to 100 degrees F.in the anaerobic digester and for farm and domestic applications.
Key components of the AD System and the Reference System are given in Tables 1 and 2, respectively.

Table 1   Components of the AD System

Item	Description	Specification
1	Plug-flow digester	$38 \times 7.6 \times 4.3$ m; 1240 m^3 volume; with hypalon cover
2	Greenhouse enclosure for digester	$40 \times 10 \times 3$ m; with a double polyethylene cover
3	Engine-Generator set; with waste heat recovery heat exchanger	Caterpillar G3306 biogas engine; 85 kW electric generator
4	Manure collection-mix tank	4.6 m diameter; 3.0 m depth; 50 m^3 volume
5	Effluent tank	4.6 m diameter; 3.0 m depth; 50 m^3 volume
6	Solid-Liquid separator	Vibrating screen separator on a steel platform; capacity 3.03 m^3/kWh
7	Solids drying bed	25 x 8 m concrete platform
8	Wastewater storage basin	$70 \times 70 \times 5$ m; 24,500 m^3 volume
9	Bobcat® front loader	30 kW engine
10	Pumps	15 kW, 3.75 kW, and 1.0 kW
11	Mixers	15 kW and 3.75 kW
12	Gas blower/compressor	1.0 kW
13	Piping for biogas, wastewater, and manure	15-cm PVC pipe; 7.5-cm PVC pipe; and 6.3-cm black steel pipe

Table 2   Components of the Reference System

Item	Description	Specification
1	Manure collection-mix tank	4.6 m diameter; 3.0 m depth; 50 m^3 volume
2	Solid-Liquid separator	Vibrating screen separator on a steel platform; capacity 3.03 m^3/kWh
3	Solids drying bed	25 x 8 m concrete platform
4	Manure storage basin	$70 \times 70 \times 5$ m; 24,500 m^3 volume
5	Bobcat® front loader	30 kW engine
6	Pumps	15 kW
7	Mixers	15 kW
8	Piping for manure	15-cm PVC pipe

Operation of the AD System

The daily operations of the AD System begin with a diesel-powered skid loader scraping the manure from the freestalls into a collection/mix tank. The manure is mixed with water and agitated using a 15-kW mixer to form a slurry with a solids content of between 11 and 14 percent.. The manure slurry is pumped into the plug flow digester through a 15-cm PVC pipe using a 15-kW pump. An equal volume of digester effluent is displaced from the digester and flows into the effluent tank. The effluent is mixed using a 3.75 kW mixer and then a 3.75-kW pump delivers the effluent to a vibrating screen separator. The separated solids are dried on a

concrete bed and used as bedding and soil conditioner. The wastewater from the separator flows into an earthen wastewater storage basin from where it is pumped into a field of corn. The wastewater supplies nutrients to the corn significantly reducing the demand for chemical fertilizer. (The Langerwerfs report a better than 20 percent increase in yield of corn with the AD System.) Biogas collects below the digester hypalon cover and a 1.0-kW blower delivers it to a gas engine that delivers power to a generator. The waste heat from the engine is recovered using a heat exchanger that delivers hot water to a storage tank. A 1.0 kW pump circulates the hot water in a 6.4-cm black steel pipe through the digester. The hot water is also used for other purposes on the dairy farm. Figure 1 is a schematic diagram of the AD System.
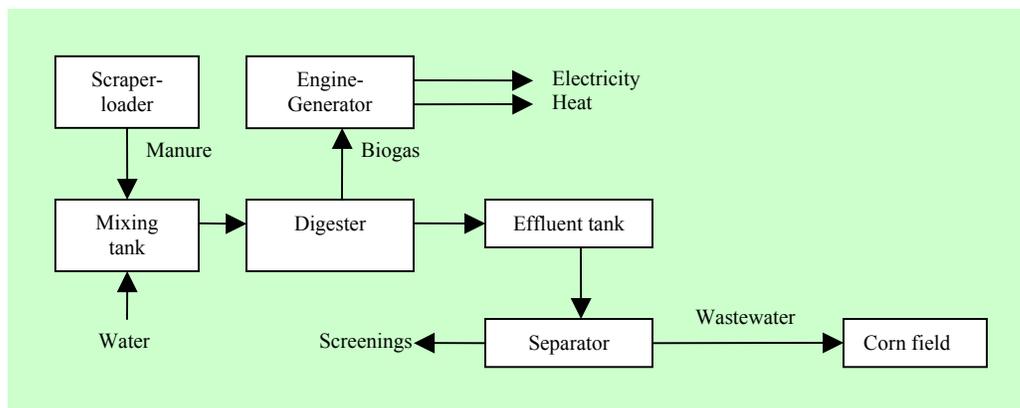
Figure 1 Schematic diagram of the AD System

Operation of the Reference System

The daily operations of the Reference System are similar to those of the AD System except for those operations associated with the AD System. The daily operations start with a diesel-powered skid loader scraping the manure from the freestalls into a manure collection/mix sump. Water is added to the manure and the mixture is mixed thoroughly using a 15-kW mixer to form slurry. The manure slurry is pumped into a vibrating screen separator using a 3.75-kW pump. The separated solids are dried on a concrete bed and used as bedding and soil conditioner. The wastewater from the separator flows into an earthen wastewater storage basin through a 15-cm PVC pipe and is used as irrigation water for corn. A 15-kW irrigation pump and a 15-cm PVC pipe are used in the irrigation system. The wastewater supplies nutrients to the corn crop and therefore reduces the need for chemical fertilizer. Figure 2 is a schematic diagram of the Reference System.
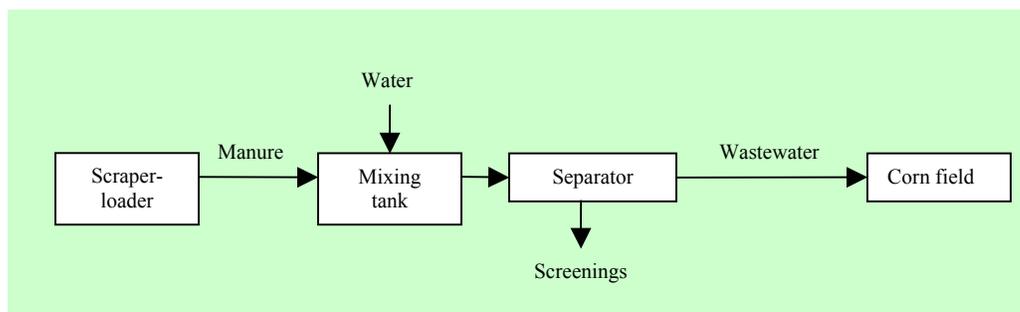
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Figure 2   Schematic diagram of the Reference System

Specifications for both systems

The AD System was installed in 1981 and in 1998 the system was refurbished. During the past 22 years, the average annual electricity output has been about 320,000 kWh and the average annual thermal energy output has been about 2.6×10^6 MJ. A summary of the specifications for the AD and the Reference systems are presented in Table 3.

Table 3. Specifications for the AD and Reference systems

Item	Parameter	AD System	Reference System
1	Number of cows	400	400
2	Average weight of cow (kg)	600	600
3	Total quantity of manure (kg/d)	20,640	20,640
4	Total manure volatile solids (kg/d)	2,400	2,400
5	Manure dilution water volume (m^3/d)	20.8	20.8
6	Digester feed volume (m^3/d)	41.7	0
7	Volume of digester (m^3)	1,239	0
8	Hydraulic retention time (days)	30	0
9	Biogas production (m^3/d)	576	0
10	Methane production (m^3/d)	346	0
11	Biogas heating value (MJ/m^3)	20.2	0
12	Grid electricity (kWh/d)	0	652
13	Electricity generation (kWh/d)	872	0
14	Heat production (MJ/d)	7,000	0
15	Natural gas consumption (m^3/d)	0	23.2
16	Wastewater volume (m^3/d)	34.4	34.4
17	Volatile solids in wastewater basin (kg/d)	240	2,400
18	Applied nitrogen (kg/d)	81	81
19	Nitrogen available to crops (kg/d)	56.7	48.6
20	Dry screenings (kg/d)	1,858	1,858

Estimation of GHG emissions

The study involved an analysis of the materials use and energy consumption and the associated GHG emissions of the AD and the Reference systems over four distinct life cycle phases: (1) acquisition of materials and energy, (2) construction, (3) operation, and (4) end-of-life. The materials acquisition phase consists of the production and transportation of all materials and energy required for building the DWM system. The construction phase consists of all the activities required in the fabrication of the livestock waste management systems. The operation phase encompasses all activities related to the use of the DWM system over an assumed life of 50 years. The operation phase also consists of the manufacture and transportation of all materials required to maintain and refurbish the systems. The end-of-life phase inventories the eventual demolition of the systems, and includes the actual dismantling of the systems, the transportation of the waste materials to recycling operations and landfills,

and the restoration of the land. Figure 3 shows the four life cycle phases and the boundaries for the LCA. Figures 4 and 5 show the operations of the DWM systems.
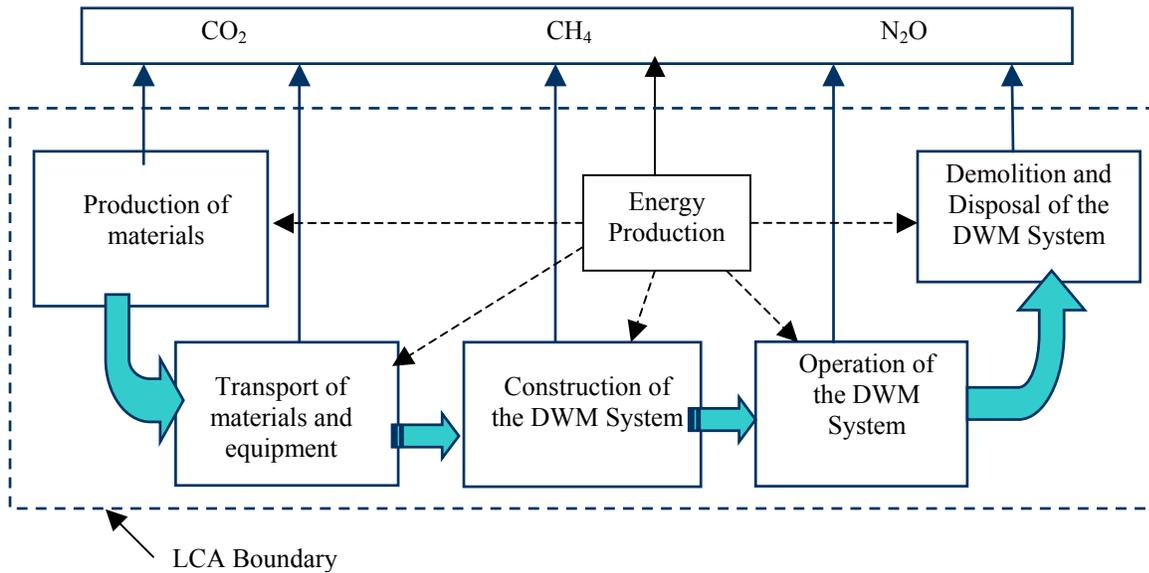

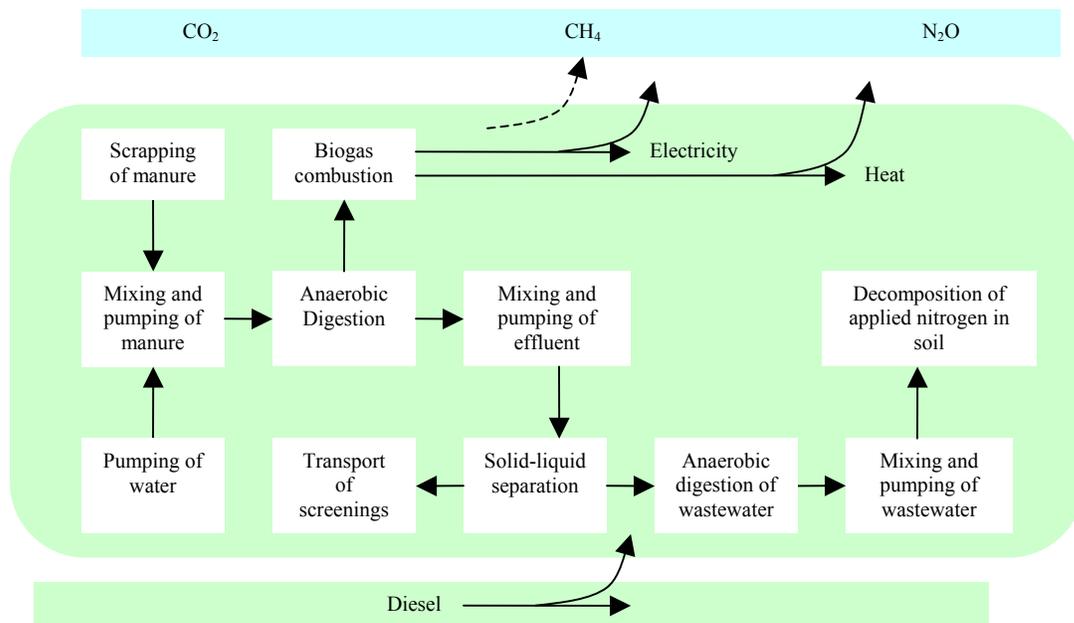**Figure 3**   LCA boundary and system life-cycle phases

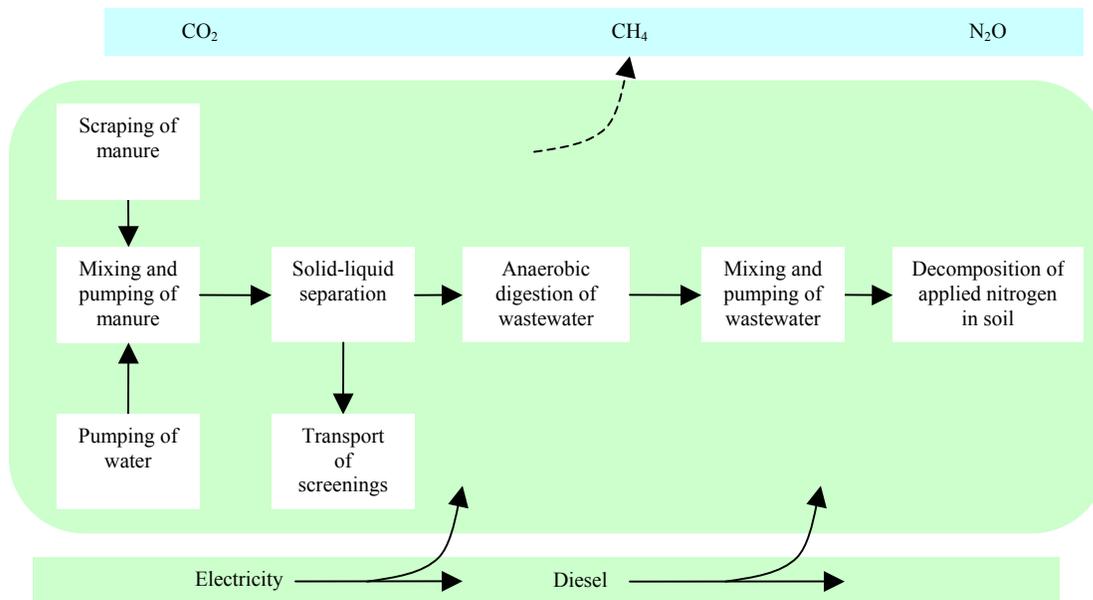**Figure 4**   Operation of the AD system

Figure 5   Operation of the Reference System

Upstream GHG emissions associated with the production and transportation of input materials and energy and those associated with the construction, operation, maintenance, demolition, and disposal activities were evaluated based on published data from several papers dealing with the subject of GHG emissions. A listing of some of these papers is given at the end of this paper. An inventory of all the materials and energy consumption in the processes and activities allowed the estimation of GHG emissions using known values of emission factors.

The study also estimated the GHG emissions that were avoided by the AD System and the Reference System. Avoided emissions included those associated with the production of commercial fertilizer, the combustion of natural gas for heating water, and the generation of electricity at the local utility power plant. The field application of livestock wastewater and manure replaced an equivalent amount of chemical fertilizer and hence avoided the emissions of GHGs associated with the production of the fertilizer.

Global warming potentials
The carbon dioxide, methane, and nitrous oxide emissions obtained from the study were converted into global warming potentials (GWP) with units of kg CO_2-equivalent (kg CO2-e) by using the following conversions: 1 kg CO_2 = 1 kg CO_2-e GWP; 1 kg CH_4 = 21 kg CO_2-e GWP; and 1 kg N_2O = 310 kg CO_2-e GWP(IPCC, 1996). By summing the GWPs, the combined effect of the CO_2, CH_4, and N_2O emissions on the global environment was expressed as a single unit of measure.

An inventory of materials, processes and activities

Table 4 lists the inventory of materials required for the construction of the AD and Reference systems for the entire 50-year life.

Table 4   Inventory of materials for DWM systems

		50-Year Life Cycle Mass (kg)	
Item	Material	AD	Reference
1	Iron/Steel	76,572	17,390
2	Cement	37,351	12,698
3	Fine Aggregate	87,152	29,628
4	Coarse Aggregate	190,960	96,501
5	Water for concrete	52,914	17,989
6	Concrete	311,256	105,816
7	PVC Pipes	4,816	3,406
8	Polyethylene covering	2,930	0
9	Hypalon Material	9,361	0
10	Electrical equipment	2,500	500

GHG emissions during the production of materials

The GHG emissions for the production of materials were estimated by multiplying the mass of material by the emission factors listed in Table 5. These emission factors were considered baseline values for the analysis. The methane and nitrous oxide emission factors for the production of the materials were very small and in some cases were not available.

Table 5   GHG Emission Factors*

Material/Process	Carbon dioxide CO_2	Methane CH_4	Nitrous oxide N_2O
Iron/steel (kg/kg)	3.58	0.00404	-
Cement (kg/kg)	1.25	-	-
Fine aggregate (kg/ton)	5.73	0.00025410	0.00019105
Coarse aggregate (kg/ton)	5.73	0.00025410	0.00019105
PVC Pipes (kg/kg)	7.60	-	-
Polyethylene sheet (kg/kg)	7.60	-	-
Hypalon sheet (kg/kg)	7.60	-	-
Electrical equipment (kg/kg)	14.31	-	-
Fertilizer (N) production (kg/kg)	1.60	-	-
Electricity production (kg/kWh)	0.138	0.000000408	0.000000318
Livestock wastewater basin (kg/kg VS)	0.11	0.06	-
Diesel engines (kg/MJ)	0.0776	0.00000344	0.00000259

*Data from several sources including: AGO (2000), IPCC (1996), EIA (2001), TDN Encyclopedia (2003), Hynes (2000), Lenzen (1999), Petersen and Solberg (2002), Environment Canada (2001), and USEPA (2000)

GHG emissions during transportation of materials

Materials that were required in the construction of the dairy waste management systems were transported by road using heavy diesel trucks. Excavated soil from the construction site was taken to a site 2 km away. Disposal of waste materials is at a landfill located 50 km away from the dairy farm. Manure screenings not needed as bedding material are applied to a corn field 2 km away from the livestock farm. The CO_2 emission for diesel trucks was estimated

to be 1.20 kg CO_2/km based on a fuel consumption of 2.50 km/L (TDN Encyclopedia, 2003) and an emission factor of 3.0 kg CO_2/litre of diesel (IPCC, 1996; Environment Canada, 2001; Hynes, 2000; Petersen and Solberg, 2002; AGO, 2000). Table 6 gives the estimated distances, truck loads and fuel efficiency associated with the transport or haulage of materials to and from the dairy farms.

Table 6   Transportation distances, truck loads and fuel efficiency

No	Operation	Distance (km)	Load (tons/truck)	Fuel Efficiency (km/L)
1	Transport of materials to dairy farm	100	8	2.5
2	Haulage of excavated soil	2	20	2.5
3	Haulage of used beddings	2	20	2.5
4	Transport of materials to disposal site	50	8	2.5
5	Haulage of backfill soil to farm	20	20	2.5

GHG emissions associated with processes and activities

The GHG emissions processes, activities, and operations were based on estimates of energy consumption.. All excavation work at the construction site was done using diesel-powered excavators. The mixing and pouring of concrete was done using diesel-powered mixers and pumps. The carbon dioxide emission factor for stationary diesel engines was estimated to be 0.0776 kg CO_2/MJ based on a CO_2 emission factor of 3.0 kg/L and a diesel heating value of 38.7 MJ/L (AGO, 2000). Mixing and pumping of water, manure, effluent, and wastewater is done using electric pumps. The baseline CO_2 emission factor for grid electricity was taken to be 0.138 kg CO_2/kWh. This factor is the updated California state-wide electricity emission factor (EIA, 2001). The emission factors for electricity production from biogas engines is assumed to be comparable with grid electricity.

Heating water for the Reference System was with natural gas with a CO_2 emission factor estimated to be 2.90 kg CO_2/m^3 (AGO, 2000). The emission of nitrous oxide associated with land application of manure was estimated from the baseline emission rate of 0.0125 kg N_2O/kg N applied (IPCC, 1996). The methane emissions from manure and wastewater storage basins were estimated from the methane production rate during anaerobic digestion. The maximum methane production rate from cow manure is estimated to be 0.24 m^3/kg volatile solids (VS) (USEPA, 2000; IPCC, 2000). The actual quantity of GHG emissions from cow manure is determined by the value of the methane conversion factor (MCF) which is in turn determined by the conditions in the storage basin. For this analysis the baseline emission factors were 0.11 kg CO_2/kg VS and 0.06 kg CH_4/kg VS. Under conditions of manure decomposition in an open storage basin, the amount of CO_2 produced is twice that of the CH_4 by weight.

End-of-life GHG emissions

The GHG emissions for the end-of-life phase only included the emissions from the demolition of the structures, the final disposal of the manure and slurry, the transportation of waste material to landfill and recycling centers, and the haulage of soil for backfilling the digester, the feed tank, the effluent tank, and the manure and wastewater storage basins. The

emissions from the recycling processes and the landfill, or any other end-of-life management processes were assumed to be negligible.

Results from the life cycle analysis
Table 7 gives an inventory of operations and their energy consumption for the AD and the Reference systems.

Table 7   An inventory of operations and their energy consumption

		Energy Consumption	
Item	Operation	AD	Reference
1	Concrete water pumping (kWh)	9.61	3.3
2	Manure dilution water pumping (kWh/d)	3.8	3.8
3	Concrete mixing energy (MJ/ton)	7.13	7.13
4	Concrete pouring/laying energy (MJ/ton)	10	10
5	Digester feed pump (kWh/d)	1.5	0
6	Mixing of manure (kWh/d)	15	15
7	Effluent mixing (kWh/d)	11.3	0
8	Effluent pumping to separator (kWh/d)	1.5	0
9	Pumping of manure to separator (kWh/d)	0	1.5
10	Solid/liquid separator (kWh/d)	13.8	13.8
11	Scraping of manure (MJ/d)	12.4	12.4
12	Wastewater basin mixing (kWh/d)	15	15
13	Biogas blower/compressor (kWh/d)	24	0
14	Digester heating water pump (kWh/d)	10	0
15	Natural gas (MJ/d)	0	915.3
16	Haulage of excavated soil (MJ/km-ton)	0.77	0.77
17	Ground excavation energy (MJ/ton)	0.22	0.22
18	Transport of materials (MJ/km-ton)	1.93	1.93
19	Spreading of beddings (MJ/km-ton)	15.5	15.5
20	Pumping of digester solids (MJ/ton)	0.25	0
21	Demolition of concrete (MJ/ton)	0.073	0.073

Tables 8 and 9 give the 50-year life cycle greenhouse gas emissions arranged by life cycle phase for the AD and Reference systems, respectively. The results show that for the AD System the GWPs for the material acquisition phase, the construction phase, and the end-of-life phase are higher than those for the Reference System. However, the GWP from the operation phase of the AD System is significantly less than that for the Reference System due to the use of the AD System. The AD System limits the emission of carbon dioxide and methane into the environment since the digestion takes place in a closed environment and the biogas produced is used for production of heat and power. The GWP associated with the generation of electricity from biogas is less than one percent of the total GWP.
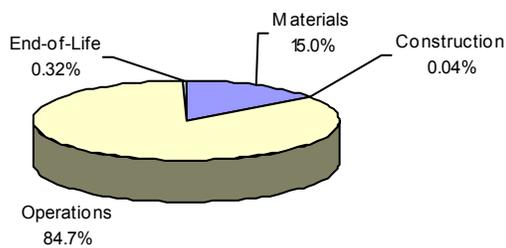
Table 8 Greenhouse gas emissions for AD System by life cycle phase for baseline conditions

| Phase	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	GWP (kg CO_2-e)
Material Acquisition	2,057,697	380	53	2,082,218
Construction	4,989	0	0	5,046
Operation	513,462	262,801	18,479	11,760,724
End of Life	43,623	2	1	44,115
TOTAL	**2,619,771**	**263,183**	**18,534**	**13,892,103**

Table 9 Greenhouse gas emissions for Reference System by life cycle phase for baseline conditions

Phase	CO_2 (kg)	CH_4 (kg)	N_2O (kg)	GWP (kg CO_2-e)
Material Acquisition	829,889	102	24	839,535
Construction	4,441	0	0	4,491
Operation	5,867,360	2,628,017	18,494	66,788,837
End of Life	38,895	2	1	39,333
TOTAL	**6,740,585**	**2,628,121**	**18,520**	**67,672,196**

Figures 6(a) and 6(b) show the contribution of the four life cycle phases to the 50-year life cycle GWP for the AD and Reference systems, respectively. The operation phase contributes the largest proportion (84.7% for the AD System and 98.7% for the Reference System) to the life cycle GWP.

(a) AD System
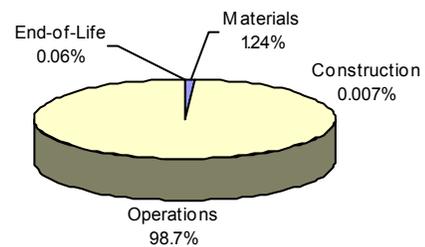
(b) Reference System

Figure 6. Comparison of GWP (kg CO_2-e) by life cycle phase

Table 10 gives the greenhouse gas emissions from operations of the two systems. For the AD System, the largest contributors to the emissions are the wastewater storage basin (50%) and the soil (48%). For the Reference System, the largest contribution to the emissions is from the

wastewater storage basin (90%). Since the Reference System does not have a controlled AD System, anaerobic digestion of the manure occurs mainly during storage in the basin.

Table 10 Greenhouse gas emissions from operations of the DWM systems

	AD System		Reference System	
Daily Operation	**GWP (kg CO_2-e)**	**Percentage**	**GWP (kg CO_2-e)**	**Percentage**
Manure scraping	17,717	0.1	17,717	0.03
Electricity use	170,521	1.4	127,482	0.2
Wastewater basin emission	6,010,674	50.4	60,106,740	90.0
Soil N2O emissions	5,728,219	48.0	5,728,219	8.6
Transport of used solid beddings	4,114	0.003	4,114	0.01
Natural gas use	0	0	804,566	1.2
TOTAL	**11,931,245**	**100.0**	**66,788,837**	**100.0**

Table 11 compares the GWPs for the AD System and the Reference System arranged by type of greenhouse gas. The results show that with exception of nitrous oxide, the GHG emissions from the AD System are less than those from the Reference System. The AD System reduces the carbon dioxide emissions by 61% and the methane emission by 90%. The overall result is that the AD System manages to reduce the GWP by 82%. This clearly demonstrates the benefit of incorporating an AD system in DWM systems.

Table 11. Comparison of GWP (kg CO_2-e) by type of greenhouse gas

	GWP (kg CO_2-e)		GWP
Greenhouse Gas	**AD System**	**Reference System**	**Reduction (%)***
Carbon dioxide (CO_2)	2,619,771	6,740,585	61
Methane (CH_4)	5,526,852	55,190,548	90
Nitrous oxide (N_2O)	5,745,481	5,741,064	0
Total GWP	**13,892,103**	**67,672,196**	**79**

*Emission reduction achieved by the AD System with respect to the Reference System

Figures 7(a) and 7(b) show the percentage contribution of the three greenhouse gases to the 50-year life cycle GWP for the AD System and the Reference System, respectively. For the AD System, N_2O emissions contribute the largest proportion (56%) to the life cycle GWP and for the Reference System, it is the CH_4 emissions that make the largest GWP contribution (82%) to the life cycle GWP. This shows that collecting and using biogas in an AD System significantly reduces the environmental impact of CH_4 emissions from manure storage basins.
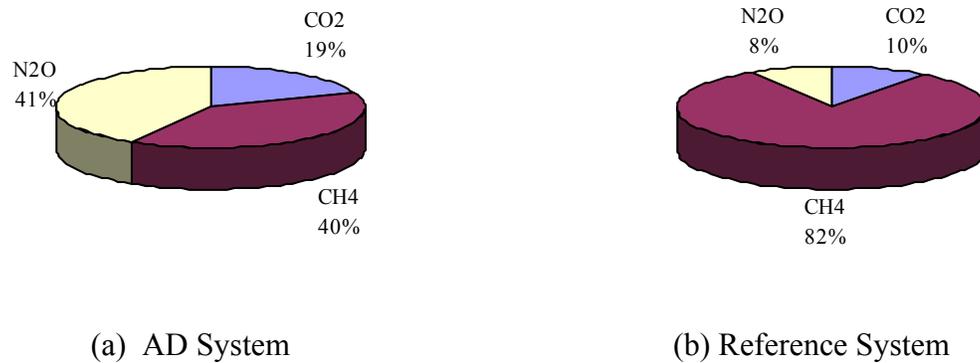

(a) AD System   (b) Reference System

Figure 7.   Comparison of GWP (kg CO_2-e) by GHG type

Effect of changes in emission factors

The results indicate that the largest contributions to the life cycle GWP are from the emissions from the manure storage basin and the nitrous oxide emissions from the corn field. Thus, the authors concluded that it was important to determine how changes in the emission factors for the wastewater storage basin and nitrous oxide affected the life cycle GWP. It was also considered important to examine the significance of changes in the emission factors for electricity production. A sensitivity analysis was conducted by varying the baseline emission factors by $\pm 50\%$ (Table 12).

Table 12   Emission factors (EF) for storage basin, electricity production, and soil nitrous oxide emissions

% Change in EF	Storage Basin EF (kg/kg VS)			Electricity Production EF (kg/kWh)			Soil EF (kg/kg N)
	CO_2	CH_4	N_2O	CO_2	CH_4	N_2O	N_2O
-50	0.055	0.03	0	0.069	0.00000020	0.00000016	0.00625
0	0.11	0.06	0	0.138	0.00000041	0.00000032	0.0125
+50	0.165	0.09	0	0.207	0.00000061	0.00000048	0.01875

Table 13 summarizes the results from the sensitivity analysis. Figures 8 and 9 show how the changes in emission factors affect the life cycle GWP for the AD and Reference systems, respectively.

Table 13   Global warming potentials with respect to changes in emission factors (EF) for wastewater storage basin, electricity generation, and soil nitrous oxide

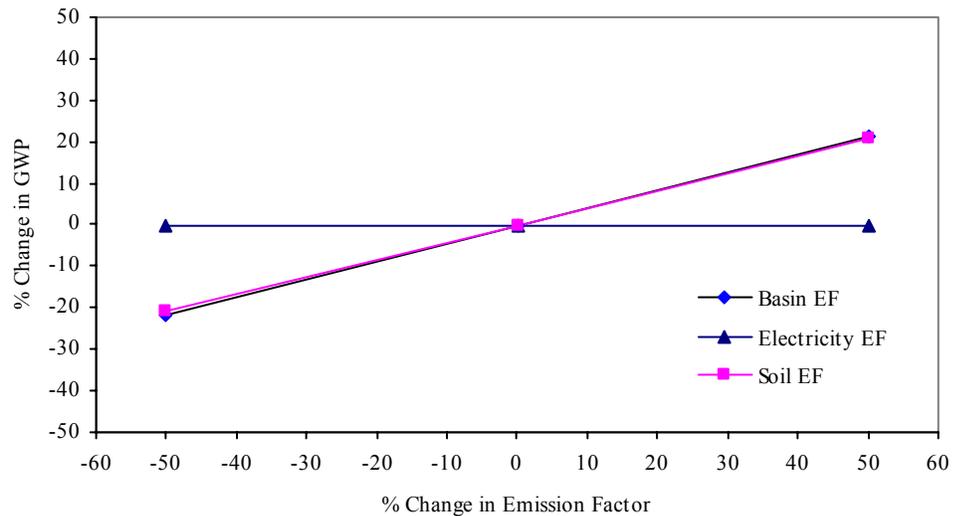| % Change	Change in Basin EF		Change in Electricity EF		Change in Soil EF	
	AD	Reference	AD	Reference	AD	Reference
-50	10,881,729	37,568,456	13,892,102	67,608,455	11,027,994	64,808,086
0	13,892,103	67,672,196	13,892,103	67,672,196	13,892,103	67,672,196
50	16,882,329	97,574,456	13,892,104	67,735,937	16,756,212	70,536,305

Figure 8   Effect of changes in basin, electricity, and soil GHG emission factors on GWP for the AD System
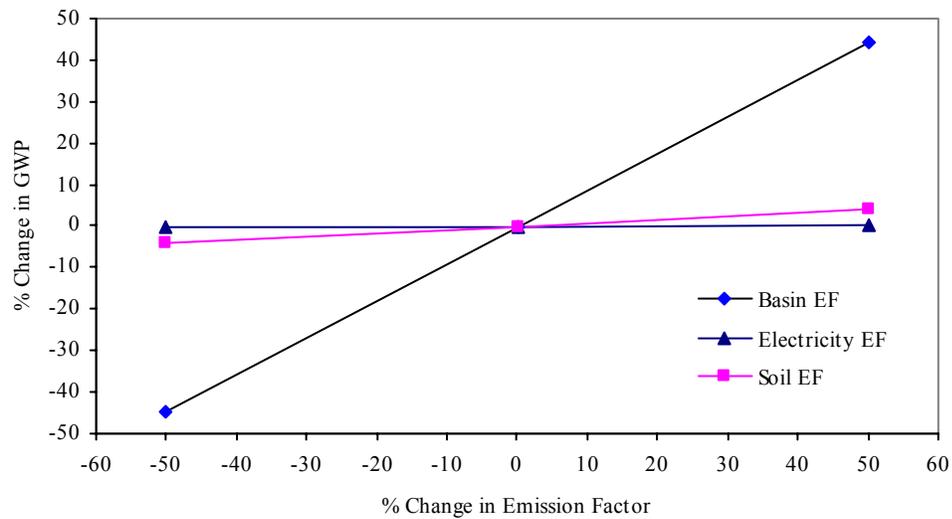
14

Figure 9   Effect of changes in basin, electricity, and soil GHG emission factors on GWP for the Reference System

The sensitivity analysis shows that the GWP for the AD System is highly sensitive to the emission factors for wastewater storage basin and soil nitrous oxide. (Table 10 indicates that emissions of soil nitrous oxide are comparable for both systems.) This is due to the fact that the GWP of the AD System is mainly made up of the emissions from the wastewater storage basin (50%) and the soil nitrous oxide (48%). Any changes in the emission factors for the wastewater storage basin and soil nitrous oxide have a significant impact on the life cycle GWP for the AD System. Changes in the emission factors for grid electricity generation have no impact on the life cycle emissions for the AD System.

The sensitivity analysis also shows that for the Reference System, changes in the wastewater storage basin make a significant impact on the life cycle GWP. The emissions from the wastewater storage basin account for about 90% of the total life cycle emissions for the Reference System. Since the emissions from soil nitrous oxide and from the use of grid electricity account for only 8.5 and 0.2% of the life cycle emissions, respectively, the life cycle GWP for the Reference System is less sensitive to changes in those emission factors.

Conclusion

On the basis of this study it can be concluded that livestock waste management systems employing Anaerobic Digestion systems reduce the Global Warming Potential by almost 80%. In addition, livestock farmers might reap financial benefits by producing electricity and hot water for farm and domestic uses and by selling the additional power into the grid.

Acknowledgements

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