Technical Appendices

Market Opportunities for Anaerobic Digestion of Livestock and Agro-Industrial Waste in India

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Appendix A: Biogas Production Potential Calculations

To estimate methane potential emissions reductions from baseline waste management systems and potential methane production from AD systems, GMI used the methodologies described in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* (*IPCC 2006 Guidelines*). This section describes the calculations and data used in the calculations.

GMI calculated the methane potential from manure using equation A-1:

$$CH_{4(M)} = \left(VS_{(M)} \times H_{(M)} \times 365\ \text{days/yr}\right) \times \left[B_{o(M)} \times 0.67\ \text{kg}\ CH_4/m^3\ CH_4 \times MCF_{S,k}\right] \qquad \text{(A-1)}$$

where:

$CH_{4\,(M)}$ = Estimated methane emissions from manure for livestock category *M* (kg CH_4 per year)

$VS_{(M)}$ = Average daily volatile solids excretion rate for livestock category *M* (kg volatile solids per animal-day)

$H_{(M)}$ = Average number of animals in livestock category *M*

$B_{o(M)}$ = Maximum methane production capacity for manure produced by livestock category *M* (m^3 CH_4 per kg volatile solids excreted)

$MCF_{(S,k)}$ = Methane conversion factor for manure management system *S* for climate *k* (decimal)

GMI calculated the methane potential for agro-industrial waste using equation A-2:

$$CH_{4(W)} = [(TOW_{(W)} - S_{(W)}) \times EF_{(W,S)}] - R_{(W)})] \qquad \text{(A-2)}$$

where:

$CH_{4\,(W)}$ = Annual methane emissions from agricultural commodity processing waste *W* (kg CH_4 per year)

$TOW_{(W)}$ = Annual mass of waste *W* COD generated (kg per year)

$S_{(W)}$ = Annual mass of waste *W* COD removed as settled solids (sludge) (kg per year)

$EF_{(W,S)}$ = Emission factor for waste *W* and existing treatment system and discharge pathway *S* (kg CH_4 per kg COD)

$R_{(W)}$ = Mass of CH_4 recovered (kg per year)

The methane emission factor in Equation A-2 is a function of the type of waste and existing treatment system and discharge pathway and is estimated using Equation A-3:

$$EF_{(w,s)} = B_{o\,(w)} \times MCF_{(s)} \quad \text{(A-3)}$$

where:

$B_{0\,(W)}$ = Maximum CH_4 production capacity (kg CH_4 per kg COD) (0.25 kg CH_4 per kg COD)

$MCF_{(S)}$ = Methane conversion factor for the existing treatment system and discharge pathway (decimal

If the annual mass of COD generated per year (TOW) is not known and the needed data cannot be collected, the remaining option is estimation using Equation A-4, with country-specific wastewater generation rate and COD concentration data obtained from the literature. In the absence of country-specific data, values listed in Table A-5 can be used as defaults to obtain first order estimates of methane emissions.

$$TOW_{(w)} = P_{(w)} \times W_{(w)} \times COD_{(w)} \quad \text{(A-4)}$$

where:

$P_{(W)}$ = Product production rate (metric tons per year)

$W_{(W)}$ = Wastewater generation rate (m^3 per metric ton of product)

$COD_{(W)}$ = Wastewater COD concentration (kg per m^3)

The data used to calculate methane potential and biogas production potential for each sector is presented below. For all calculations, methane is converted to CO_2e by multiplying by the global warming potential (GWP) of methane. For this report, GMI used a value of 25 for the methane GWP, based on IPCC estimates.

A.1 Dairy Manure

GMI used the data presented below to calculate the potential methane reductions for AD system development for dairy manure:

Variable	Description	Value: Daily Spread	Value: Burned for Fuel	Value: Liquid Slurry	Notes
$H_{(\#)}$	Total country average animal population, number of head		118,597,829		India Census data, including dairy cattle and buffalo
VS (kg/head/day)	Volatile solids excretion rate	2.6	2.6	2.6	Based on IPCC defaults
B_o (m^3 CH_4/kg VS)	Maximum methane production capacity	0.13	0.13	0.13	Based on IPCC defaults
MCF	Methane conversion factor	0.04	0.1	0.65	Based on IPCC defaults
%WMS	Percent of production in waste management systems	19%	51%	1%	Based on IPCC default estimates (excluding pasture and AD systems)
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	50%	50%	50%	GMI assumes 50% of dairy manure management not in pasture or AD systems could be replaced by AD
CH_4 (metric ton/yr)	WMS Methane emissions	37,808	253,709	32,335	Calculated using Equation A-1 and the %WMS and %WMS AD
Total CH_4 (metric ton/yr)	**Total methane emissions, CH_4**		323,852		Sum of methane from daily spread, burned for fuel, and liquid/slurry systems
Total CO_2 e (metric ton/yr)	**Total methane emissions, CO_2e**		8,096,293		Total methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The $H_{(\#)}$, VS (kg/head/day), B_o (m^3 CH_4/kg VS) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 35.5 percent of manure in baseline systems that would be replaced by AD systems ((19%+51%+1%) x 50%).
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 5,137 million m^3 of biogas per year.

A.2 Poultry Manure

GMI used the data presented below to calculate the potential methane reductions for AD system development for poultry manure:

Variable	Description	Value	Notes
$H_{(\#)}$	Total country average animal population, number of head	729,209,320	India Census data
VS (kg/head/day)	Volatile solids excretion rate	0.02	Based on IPCC defaults
B_o (m^3 CH_4/kg VS)	Maximum methane production capacity	0.24	Based on IPCC defaults
MCF	Methane conversion factor	0.015	Based on IPCC defaults
%WMS	Percent of production in waste management systems	50%	Based on IPCC default estimates
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	50%	GMI assumes 50% of poultry manure management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	3,258	Calculated using Equation A-1 and the %WMS and %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	81,445	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The $H_{(\#)}$, VS (kg/head/day), B_o (m^3 CH_4/kg VS) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 50 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 929 million m^3 biogas per year.

A.3 Sugarcane Processing

GMI used the data presented below to calculate the potential methane reductions for AD system development for sugarcane processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	348,000,000	Government of India 2018
W (m^3/metric ton)	Wastewater generation rate	11.0	GMI 2011
COD (kg/m^3)	Chemical oxygen demand	3.2	Based on IPCC defaults
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.8	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	5%	GMI assumes 5% of waste management in open lagoons could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	122,496	Calculated using Equation A-1 and the %WMS AD
Total CO_2e (metric ton/yr)	Methane emissions, CO_2e	3,062,400	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 5 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 328 million m^3 biogas per year.

A.4 Distilleries

GMI used the data presented below to calculate the potential methane reductions for AD system development for distilleries:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	3,550,500	USDA GAIN
W (m^3/metric ton)	Wastewater generation rate	12.0	GMI 2011
COD (kg/m^3)	Chemical oxygen demand	110	GMI 2011
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.15	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	5%	GMI assumes 5% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	8,787	Calculated using Equation A-1 and the %WMS AD
Total CO_2e (metric ton/yr)	Methane emissions, CO_2e	219,687	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 5 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 125 million m^3 biogas per year.

A.5 Milk Processing

GMI used the data presented below to calculate the potential methane reductions for AD system development for milk processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	33,080,800	Milk production, National Dairy Development Board; 20% processed, Mehrotra et al. 2016
W (m^3/metric ton)	Wastewater generation rate	7.0	Based on IPCC defaults
COD (kg/m^3)	Chemical oxygen demand	2.7	Based on IPCC defaults
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.15	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	5%	GMI assumes 5% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	1,172	Calculated using Equation A-1 and the %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	29,308	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 5 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 17 million m^3 biogas per year.

A.6 Fruit and Vegetable Processing

GMI used the data presented below to calculate the potential methane reductions for AD system development for fruit and vegetable processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	5,635,040	Fruit and vegetables processed, National Horticulture Board; 2% processed, USDA GAIN
W (m^3/metric ton)	Wastewater generation rate	20.0	Based on IPCC defaults
COD (kg/m^3)	Chemical oxygen demand	5	Based on IPCC defaults
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.8	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	9%	GMI assumes 9% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	10,143	Calculated using Equation A-1 and the %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	253,577	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 9 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 27 million m^3 biogas per year.

A.7 Cornstarch Production

GMI used the data presented below to calculate the potential methane reductions for AD system development for cornstarch processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	1,800,000	Production, USDA GAIN
W (m^3/metric ton)	Wastewater generation rate	5.0	Expert judgment
COD (kg/m^3)	Chemical oxygen demand	20	Expert judgment
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.8	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	14%	GMI assumes 14% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	5,040	Calculated using Equation A-1 and the %WMS AD
Total CO_2e (metric ton/yr)	Methane emissions, CO_2e	126,000	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 14 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 13 million m^3 biogas per year.

A.8 Tapioca Production

GMI used the data presented below to calculate the potential methane reductions for AD system development for tapioca processing:

Variable	Description	Value	Notes
P (metric ton/yr)	Product production rate, country total	79,200	Production, Government of India 2018; 1.6% tapioca turned into starch, GMI 2011
W (m^3/metric ton)	Wastewater generation rate	4.0	Expert judgment
COD (kg/m^3)	Chemical oxygen demand	11	Expert judgment
B_0 (kg CH_4/kg COD)	Maximum methane production capacity	0.25	Based on IPCC defaults
MCF	Methane conversion factor	0.8	Based on IPCC defaults
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	17%	GMI assumes 17% of waste management could be replaced by AD
CH_4 (metric ton/yr)	Methane emissions, CH_4	118	Calculated using Equation A-1 and the %WMS AD
Total CO_2 e (metric ton/yr)	Methane emissions, CO_2e	2,962	Methane emissions multiplied by GWP of methane

GMI calculated the biogas production using:

- The P, W (m^3/metric ton), COD (kg/m^3), B_o (kg CH_4/kg COD) shown above,
- An assumed MCF of 0.8 for an AD system,
- Multiplication by the 17 percent of manure in baseline systems that would be replaced by AD systems.
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 0.3 million m^3 biogas per year.

A.9 Crop Residues

GMI used the data presented below to calculate the potential methane reductions for AD system development for crop-residues:

Variable	Description	Value	Notes
W (million ton/year)	Surplus crop-residues production, country total	178	TIFAC & IARI data (2018)
VS (kg/kg of crop residues)	Volatile Solids rate	0.70	USDA (2008)
B_o (kg CH_4/kg VS)	Maximum methane production capacity	0.36	Contreras et al. (2012), Yan et al. (2017)
%WMS AD	Assumed percent of production of each WMS that could be replaced by AD	25%	GMI assumes 25% of crop-residues could be replaced by AD

GMI calculated the biogas production using:

- The W (million metric ton/year), VS (kg/kg crop residues), and B_o (kg CH_4/kg Vs) shown above, and
- An assumption that 25 percent of crop residues could be replaced by AD (%WMS AD).
- An assumption of 55% methane in biogas, and a density of 0.68 kg/m^3 of methane.

The resulting value is 29,983 million m^3 biogas per year.

Appendix B: Indirect Emissions Reduction Calculations

GMI used the electricity generation potential of biogas and the emissions rate associated with the offset fuel source to estimate indirect emissions reductions from offsetting electricity generation from traditional fossil fuels. GMI assumed that the biogas would replace coal as the fuel for electricity generation. This section describes the calculations and data used in the calculations.

GMI calculated the electricity generation potential from biogas using equation B-1:

$$\text{Elec. Gen. Potential} = CH_4 \text{ Production Potential} / \text{Methane Density} \times CH_4 \text{ Heat Content} / \text{Btu to Wh Conversion} \times \text{Engine Efficiency} \times \text{Online Efficiency} / \text{Wh to kWh Conversion} \quad \text{(B-1)}$$

where:

Elec. Gen. Potential	=	Electricity generation potential from biogas (kWh/year)
CH_4 Production Potential	=	Methane production potential (MT CH_4 per year)
Methane Density	=	Density of methane (metric ton CH_4/ft^3 CH_4)
CH_4 Heat Content	=	Heat content of the methane (Btu/ft^3 CH_4)
Btu to Wh Conversion	=	Energy conversion factor from British thermal units to watt hours (Btu/Wh)
Engine Efficiency	=	Assumed engine efficiency (%)
Online Efficiency	=	Assumed online efficiency (%)
Wh to kWh Conversion	=	Energy conversion factor from watt hours to kilowatt hours (Wh/kWh)

GMI calculated the indirect emission reductions using Equation B-2:

$$CH_4 \text{ Reductions}_{Indirect} = \text{Elec. Gen. Potential} \times CO_2 \text{ Emission Reduction} \quad \text{(B-2)}$$

where:

CH_4 $\text{Reductions}_{Indirect}$	=	Indirect emission reductions from replacing coal with biogas for electricity generation (MT CO_2 per year)
Elec. Gen. Potential	=	Electricity generation potential from biogas (kWh/year)
CO_2 Emission Rate	=	CO_2 emissions rate from generating electricity with coal (kg CO_2/kWh generated)

Using equation B-1, GMI calculated that 14.8 million metric tons of CO2e could be reduced due to avoided coal-generated power plant emissions.

B.1 Indirect Emissions Values

GMI used the following assumptions and conversion factors to calculate the indirect emissions reductions from biogas use for electricity generation:

- Methane density: 1.92E-05 metric ton CH_4 per ft^3 CH_4
- Assumed heat content of methane: 923 Btu/ft^3 CH_4
- Energy conversion factor: 3.413 Btu per Wh
- Assumed engine efficiency: 0.35
- Assumed online efficiency: 0.9
- Energy conversion factor: 1000 Wh per kWh

GMI then used the above assumptions with the methane production potential calculated in Appendix A to determine electricity generation potential and indirect emissions reductions:

Sector	Methane Production Potential (MT CH_4 per year)	Electricity Generation Potential (kWh per year)	Indirect Emissions Reduction (MT CO_2e per year)
Dairy Manure	2,825,619	12,536,846,095	12,787,583
Poultry Manure	347,500	1,541,806,792	1,572,643
Sugarcane Processing	122,496	543,496,367	554,366
Distilleries	46,867	207,940,070	212,099
Milk Processing	6,252	27,740,389	28,295
Fruit and Vegetable Processing	10,143	45,003,288	45,903
Cornstarch Production	5,040	22,361,724	22,809
Tapioca Production	118	525,692	536

B.2 Other CO_2 Emission Reduction Values

Indirect emissions reduction from offsetting other fossil fuels can be calculated by using an appropriate emissions rate. In India, the electricity sector generation mix is comprised of thermal plants (60 percent), hydroelectric plants (34 percent), and nuclear plants (6 percent; GMI 2011). The principal fuels used by thermal plants are coal, fuel oil, and natural gas. The table below shows the associated carbon emissions rate for each fuel type.

Fuel Replaced	CO_2 Emission Reduction
Coal	1.02 kg/kWh generated
Natural gas	2.01 kg/m^3 CH_4
LPG	2.26 kg/m^3 CH_4
Distillate fuel oil	2.65 kg/m^3 CH_4

Source: GMI 2011