

Supplementary Information: Feasibility of Grass-to-Gas on Dairy Farms: A Probabilistic Techno-Economic Comparison of Renewable Natural Gas and Electricity Production

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S1 Feedstock Characterization and System Streams

S1.1 Dairy manure

The baseline dairy farm was modeled with a herd size of 1,000 cows (N_{cows}). All are assumed to be adult cows, classified into dry and lactating cows with no heifers or calves included. Based on reported herd composition, 85% are lactating (f_{lact}) [1, 2].

Wastewater produced from the milking parlor was assumed to be combined with barn manure in a lagoon. Barn waste was assumed to be scraped without using flush water. Parlor cleaning was modeled as a hose system [3]. Equation S1 was adapted to estimate the wastewater flow (F_{ww} , gal d⁻¹) as function of herd size [3].

$$F_{\text{ww}} = 477.5 + (0.625 N_{\text{cows}}) \quad (\text{S1})$$

The wastewater flowrate was converted to kg d⁻¹ using a water density of 1000 kg m⁻³.

The total manure flowrate (F_{manure}) entering the system was calculated as the weighted sum of manure from dry and lactating cows plus the generated wastewater:

$$F_{\text{manure}} = N_{\text{cows}} (1 - f_{\text{lact}}) F_{\text{dry}} + N_{\text{cows}} f_{\text{lact}} F_{\text{lact}} + F_{\text{ww}} \quad (\text{S2})$$

F_{dry} and F_{lact} are the manure production rates per cow dry and lactating cow, respectively (see Table S1). The total manure flowrate was converted to kg h⁻¹ for simulation consistency.

Dairy manure was modeled as a mixture of manure streams from dry cows and lactating cows, with the overall composition determined by the composition and relative quantities of each stream. The resulting dairy manure composition used in the process is detailed in Table S1. Physical and thermophysical properties of dairy manure are shown in Table S2.

Table S1 Dairy manure flowrate and composition.

Parameter	Dry cow ¹	Lactating cow ¹	Dairy manure ²	Unit
Manure production	38	68	68	kg/cow·day
Water content	87.0	87.0	87.8	% w.b. ³
Total solids	13.0	13.0	12.2	% w.b.
Volatile solids	11.1	10.9	10.3	% w.b.
Total Carbon	6.1	6.0	5.7	% w.b.
Total Nitrogen	0.6	0.7	0.6	% w.b.
C/N ratio	10.2	8.6	9.2	

¹All values for dry and lactating cow from [4], except total carbon from [5].

²Dairy manure was modeled as a mixture of manure streams from dry cows and lactating cows.

³w.b. = wet basis.

Table S2 Dairy manure physical and thermophysical properties.

Parameter	Symbol	Dairy manure	Units	Reference
Inlet temperature	T_{in}	20	°C	[6]
Density	ρ	1,001.86	kg/m ³	[7]
Viscosity	μ	0.92	Pa·s	[8]
Heat capacity	C_p	2.68	kJ/kg·°C	[9]
Thermal conductivity	k	0.60	W/m·°C	[9]

S1.2 Lignocellulosic feedstocks

Three lignocellulosic feedstocks are considered: corn stover (*Zea mays*), switchgrass (*Panicum virgatum*), and winter rye (*Secale cereale*). Each crop has two source options: on-farm grown and purchased. In the on-farm scenario, the dairy farm grows its own crop for the AD system. Meanwhile, for the purchased scenario biomass was purchased from an external source.

In the model and throughout the text, the feedstocks are abbreviated as follow: corn stover (CORN), switchgrass (SWG), and winter rye (WR). Once a specific feedstock was selected, it was referenced in the model as *grass*, which represents the chosen lignocellulosic feedstock.

The composition and physical properties of the biomass used in the model are detailed in Tables S3 and S4.

Table S3 Lignocellulosic feedstocks composition and characteristics.

Parameter	CORN ¹	SWG ²	WR ³	Units
Water content	5.2	15.0	4.1	% w.b.
Total solids	94.8	85.0	95.9	% w.b.
Volatile solids	88.0	77.5	88.5	% w.b.
Total carbon	43.3	46.5	37.0	% w.b.
Total nitrogen	0.6	0.4	1.0	% w.b.
C/N ratio	67.6	116.2	37.0	

¹Composition from [10].

²Total solids and volatile solids from [11]. Total carbon and nitrogen from [12].

³Water content, total solids, and volatile solids from [13]. Total carbon and nitrogen from [14].

Table S4 Lignocellulosic feedstocks physical and thermophysical properties.

Parameter	Symbol	CORN ²	SWG ³	WR ⁴	Units
Inlet temperature ¹	T_{in}	14	14	14	°C
Particle density	ρ	861.70	1,195.00	1,195.00	kg/m ³
Heat capacity	Cp	1.67	1.44	1.45	kJ/kg.°C
Thermal conductivity	k	0.20	0.62	0.62	W/m.°C

¹Inlet temperature correspond to Pennsylvania average temperature through the year [15].

²Particle density was taken from [16]. Heat capacity was obtained from [17]. Thermal conductivity was obtained from [18].

³Particle density was taken from [19]. Heat capacity and thermal conductivity were obtained from [20].

⁴Particle density and thermal conductivity were assumed to be the same as switchgrass. Heat capacity was obtained from [21].

On-farm biomass scenario

In the on-farm scenario, the cropland area (A_{farm} , ac cow⁻¹) was estimated as 1.5 acres per cow [2]. A fraction of this land ($f_{land,i}$) was dedicated to each feedstock according to the assumptions of the scenario. For corn stover, 50% of the cropland was designated for corn grain. Switchgrass was assumed to be grown on 50% of the cropland, leaving the remaining land available for feed. Winter rye was grown as a cover crop,

using 70% of the cropland during winter; the remaining 30% is typically dedicated to perennial crops such as haylage or alfalfa [22]. The total area for feedstock i was calculated as:

$$A_i = A_{\text{farm}} N_{\text{cows}} f_{\text{land},i} \quad i = \text{CORN, SWG, WR} \quad (\text{S3})$$

Where N_{cows} is the herd size.

The yield of each crop (Y_i , d.m. Mg ac⁻¹ yr⁻¹) was obtained from literature. Corn yield corresponds to the U.S. national average for 2025 [23], switchgrass assumes full productivity which is achieved after the third year [24], and winter rye is grown after corn grain before full maturity to ensure cellulosic content for further incentives [25, 26]. The total annual production is calculated as:

$$Y_{\text{ann},i} = A_i Y_i \quad i = \text{SWG, WR} \quad (\text{S4})$$

For corn stover, a residue to grain ratio (R) of 1.0 was used to obtain the above ground biomass to be collected, and a yield of 0.7 d.m. Mg ac⁻¹ of residue was left in the field for conservation allowance (Y_{res}) [27]. It has been reported that 30-40% of corn residue can be collect after harvest to maintain and enhance soil quality, and the yield used fulfills that requirement [28, 29]. Therefore, the annual corn that can be collected is calculated by:

$$Y_{\text{ann, corn}} = A_{\text{corn}} Y_{\text{corn}} R - (Y_{\text{res}} A_{\text{corn}}) \quad (\text{S5})$$

Biomass losses during field operations (L_{field}) and storage (L_{storage}) were also accounted for in the model. Literature reports up to 30% field losses for baled biomass and additional 0-15% losses during storage depending on conditions [27, 30, 31]. In this project, all harvested biomass undergoes field operations and is stored to supply the digester for one year. It is assumed that biomass is covered with a plastic tarp and stored outside for a maximum of eleven months, while one month of feedstock is stored in a pole barn prior to digestion. Consequently, since part of the bales are outside (covered) and part inside the pole barn, an overall 6% d.m. loss was assumed in the model. Equation S6 calculates the annual feedstock flowrate of each feedstock on a wet basis.

$$F_{\text{ann},i} = \frac{Y_{\text{ann},i} (1 - L_{\text{field}})(1 - L_{\text{storage}})}{1 - x_{\text{moisture},i}} \quad i = \text{CORN, SWG, WR} \quad (\text{S6})$$

The denominator term converts the dry-matter yield to an equivalent wet-basis flowrate, where $x_{\text{moisture},i}$ is the moisture fraction of each feedstock as reported in Table S3. The resulting annual production ($F_{\text{ann},i}$) was converted to the corresponding feedstock flowrate (F_i) used in the simulation, assuming continuous operation throughout the year. The model operates on an hourly basis while the on-farm feedstock availability is estimated annually; therefore, both flowrates are reported for direct comparison across scenarios. Table S5 summarizes the feedstock production in the on-farm scenario described above.

Table S5 Lignocellulosic feedstocks production for on-farm scenario.

Parameter	Symbol	CORN	SWG	WR	Units
Land allocation	$f_{\text{land},i}$	0.5	0.5	0.7	
Crop area	A_i	303	303	424	ha
Yield	Y_i	11.7	15.7	9.0	d.m. Mg/ha-yr
Residue to grain	R	1.0			
Residue left	Y_{res}	0.7			d.m. Mg/ac
Field loss	L_{field}	30	30	30	% d.m.
Storage loss	L_{storage}	6	6	6	% d.m.
Annual flowrate	$F_{\text{annual},i}$	2,095	3,686	2,621	w.b. Mg/yr
Flowrate	F_i	240	420	300	w.b. kg/h

Purchased biomass scenario

In the purchased scenario, lignocellulosic feedstock was assumed to be obtained from neighboring farms with no limitations in availability. Feedstock quantities were calculated to achieve a target C/N ratio between 20 to 30 after mixing with dairy manure. The C/N ratios of the feedstocks were taken as 68, 116, and 37 for corn stover, switchgrass, and winter rye, respectively [10, 12, 14]. Because switchgrass has the highest C/N ratio among the evaluated feedstocks, it was used to determine the maximum biomass input rate. Switchgrass reached the target C/N ratio at a feed rate of 1175 kg h⁻¹, which was then used as the reference biomass input rate for the purchased scenarios. At this input rate, corn stover achieved a C/N ratio of 26 and winter rye a C/N ratio of 20, both within the optimal range for anaerobic digestion. Equation S7 determined the flowrate of each feedstock on a desired C/N ratio.

$$F_i = \frac{F_{C, \text{manure}} - (R_{CN} F_{N, \text{manure}})}{(R_{CN} x_{N,i}) - x_{C,i}} \quad i = \text{CORN, SWG, WR} \quad (\text{S7})$$

Where F_i is the flowrate of each grass (kg h⁻¹), $F_{C, \text{manure}}$ and $F_{N, \text{manure}}$ are the carbon and nitrogen flowrate of manure (kg h⁻¹), R_{CN} is the desired C/N ratio after mixing, $x_{C,i}$ and $x_{N,i}$ are the carbon and nitrogen composition in the grass. Figure S1 shows the influence of lignocellulosic biomass flowrates on the overall C/N ratio of the AD inputs.

Carbon and nitrogen flowrates of manure and grasses were derived from the compositions in Tables S1 and S3, respectively. Table S6 shows the quantities of each feedstock that must be purchased to achieve the desired C/N ratio in the digester.

S1.3 Water

A complete mix anaerobic digester was modeled for all scenarios, operating at a maximum total solids (TS) content of 10% (TS_{target}) [32–34]. Water was added as needed to dilute the feed mixture to the TS target. The added water was assumed to be groundwater, consistent with typical operations in Pennsylvania [35].

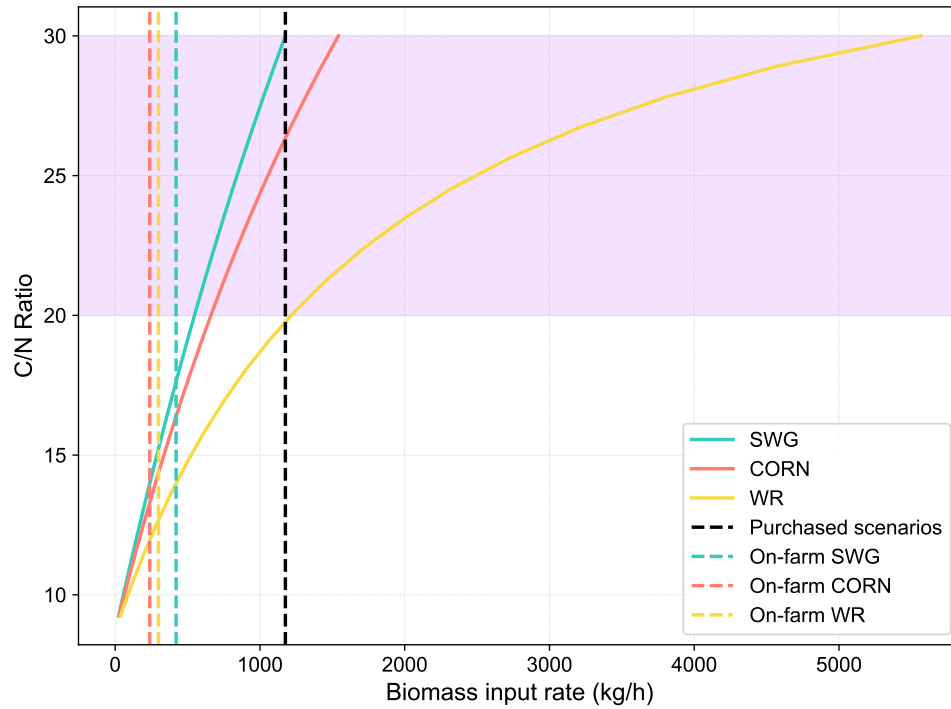


Fig. S1 C/N ratio after mixing biomass with dairy manure across a range of biomass input rates for each co-digestion scenario. Dotted colored lines represent on-farm scenarios, while the black line represents the purchased biomass scenario. SWG = switchgrass, CORN = corn stover, WR = winter rye.

Table S6 Lignocellulosic feedstocks bought for purchased scenario.

Parameter	Symbol	CORN	SWG	WR	Units
Annual flowrate	$F_{\text{annual},i}$	9,778	9,778	9,778	w.b. Mg/yr
Flowrate	F_i	1,175	1,175	1,175	w.b. kg/h

For recirculation, the water requirement was dynamically calculated within the mixing tank unit to account for the additional solids introduced by the recirculated digestate. See Section S2 for more detail. The physical and thermophysical properties of water used in the model are summarized in Table S7.

Table S7 Water thermophysical properties.

Parameter	Water	Units	Reference
Inlet temperature	10	°C	[36]
Cp	4.18	kJ/kg·°C	[37]
k	0.61	W/m·°C	[38]

S2 Unit Operations

The on-farm AD system changes regarding the final biogas end-use pathway. However, both systems include anaerobic digestion, biogas utilization, storage, pre- and post-processing operations, and auxiliary units sections. A steady-state mass balance was assumed for all units. In both cases, dairy manure and lignocellulosic biomass are processed in an anaerobic digester. The biogas produced is directed either to a combined heat and power (CHP) unit or to an upgrading process for RNG injection (Figure S2). Detailed descriptions of each unit operation are provided in the following subsections:

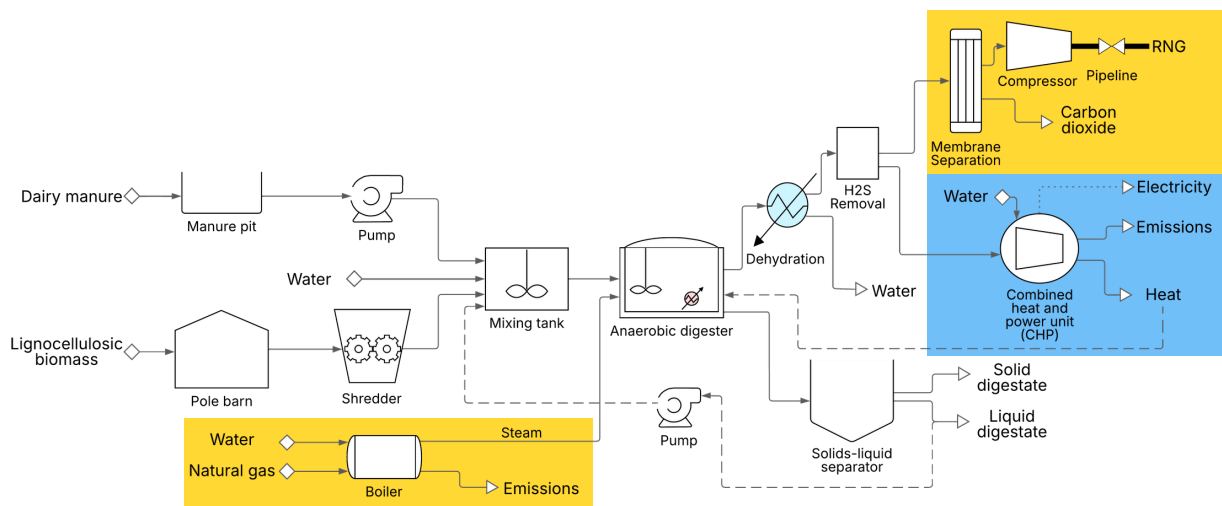


Fig. S2 AD process model for the RNG pathway (yellow) and electricity pathway (blue). Dashed lines indicate that only a fraction of the stream is processed.

S2.1 Anaerobic digestion

The anaerobic digestion process is done in a continuous stirred tank reactor (CSTR) after the dairy manure, lignocellulosic feedstock, and water are mixed in a mixing tank.

The anaerobic digester was designed to simulate a CSTR, meaning that the tank is simulated in steady-state and there is continuous mixing. The digester was built to simulate The Pennsylvania State University digester characteristics [39]. The digester is all above ground, the geometry is designed as a cylinder with a height-to-diameter ratio of 1.5, and a roof modeled as a hemisphere. The tank was designed to have an insulation layer preventing temperature drop of more than $1\text{ }^{\circ}\text{C day}^{-1}$. It has a concrete inside layer and an outside styrofoam layer on the wall. The roof is made of urethane and galvanize steel. Figure S3 illustrates the CSTR modeled in this study.

There are two agitators located on opposite sides of the digester and a heat exchanger at the bottom. The digester has a hydraulic retention time (HRT) of 22 days, is operated at mesophilic conditions ($37\text{ }^{\circ}\text{C}$), and a working volume (V_w) of 70% [33, 34, 39, 40]. The tank dimensions are automatically scaled according to the total volumetric flow of the inputs for each scenario.

Energy balances: An energy balance was developed for the anaerobic digester under the assumptions of steady-state conditions and continuous mixing. The digester operates at constant temperature, and no accumulation of energy occurs over time. The digester is simulated to have a heat exchanger at the bottom and the mixing energy is considered as a source of internal energy dissipation and is included in the thermal losses of the system.

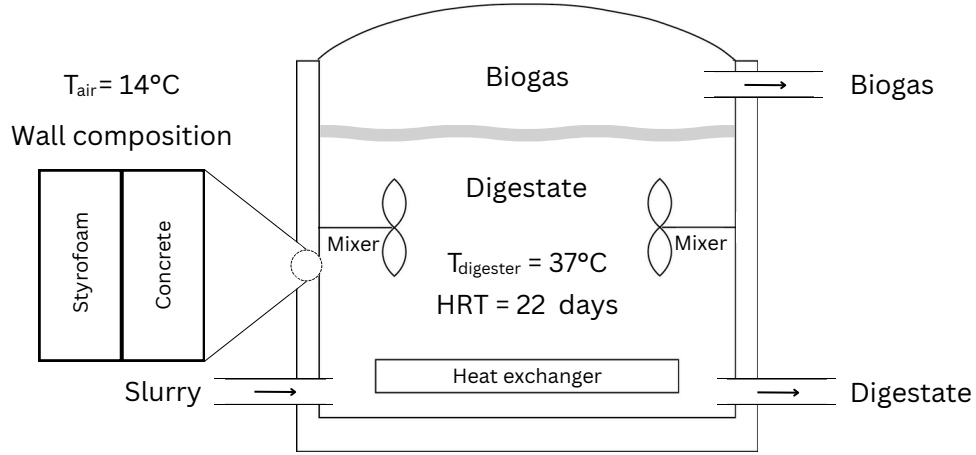


Fig. S3 Diagram of CSTR digester modeled.

The general steady-state energy balance for total heat quantities in a control volume with no work other than shaft work and no energy accumulation is given by equation S8.

$$Q_{\text{input}} = Q_{\text{heating}} + Q_{\text{loss}} \quad (\text{S8})$$

Where Q_{input} (kJ h^{-1}) is the total heat supplied by the external utilities, Q_{heating} (kJ h^{-1}) is the energy required to heat the influent to the digester operating temperature, and Q_{loss} (kJ h^{-1}) includes both thermal losses to the environment and heat dissipated from mechanical mixing. Although biogas is produced during digestion, it is not included in the digester energy balance because it forms at the reactor operating temperature and exits the system without additional heating or cooling. Its contribution to the overall heat load is considered negligible due to its low mass and heat capacity relative to the liquid phase.

The energy required to heat the slurry to the mesophilic operating temperature was calculated based on the enthalpy change of the feedstock mixture entering the digester. The system assumes negligible kinetic and potential energy. The heat required to raise the temperature of a fluid at constant pressure can be expressed as [41]:

$$Q_{\text{heating}} = F Cp \Delta T \quad (\text{S9})$$

Where F is the mass flowrate of the slurry, Cp is the specific heat capacity of that component, and ΔT is the temperature difference between the operating temperature (T_{digester}) and the inlet temperature (T_{in}) of the feed. Only the temperature change of the incoming slurry was considered in the energy balance, as the outlet temperature of the digester is assumed to be constant under mesophilic conditions.

Since the digester feed consists of a mixture of multiple feedstocks, the overall heat requirement was calculated using the individual heat contributions of the components of the mixture. Equation S10 for mass-weighted average was used to represent the overall temperature and heat capacity of the slurry.

$$X_{\text{avg}} = \frac{\sum F_i \cdot X_i}{\sum F_i} \quad i = \text{manure, grass, water} \quad (\text{S10})$$

Where X_i is the value of the parameter for feedstock i , and M_i is the corresponding mass flow entering the digester.

Heat losses from the digester to the environment occur through the tank wall and are driven by the temperature gradient between the internal slurry and the external ambient air. External air temperature is considered 14°C as this is the average temperature in Pennsylvania throughout the year [15]. The total heat transfer process is modeled as a series of thermal resistances, including internal convection from the slurry, conduction through the wall, and external convection to the air. The overall heat transfer rate is calculated using:

$$Q_{\text{loss}} = U A \Delta T \quad (\text{S11})$$

Where ΔT is the overall temperature difference between the hot and cold fluids, A is the area for heat transfer, and the overall heat transfer coefficient U . The surface area of the wall is assumed to be the same for each term, so it is canceled from the equation. The total thermal resistance R_T is expressed as Equation S12.

$$\frac{1}{U} = \frac{1}{h_{\text{slurry}}} + \frac{B_1}{k_1} + \frac{B_2}{k_2} + \frac{1}{h_{\text{air}}} \quad (\text{S12})$$

The h is the individual heat transfer coefficient of the hot and cold fluid, slurry and air respectively. The conduction term for the wall is given by the thickness B divided by the thermal conductivities k of the wall layers, concrete (1) and styrofoam (2). Then, the rate of heat transfer through the wall is given by Equation S13.

$$Q_{\text{loss}} = \frac{\Delta T}{R_T} \quad (\text{S13})$$

To find the individual heat transfer coefficient for the liquid inside the digester, empirical correlations of dimensionless numbers were used to modeled the continuous stirring tank. The system does not contains a jacket, but the slurry in contact to the wall and ambient air behaves analogously to a cooling system with a jacketed tank. Therefore, equations to simulate the jacketed stirred tank were applied to approximate the convective coefficient of the slurry (h_{slurry}) [41]. The following equations were used:

$$h_{\text{slurry}} = \frac{\text{Nu } k_{\text{fb}}}{D} \quad (\text{S14})$$

$$\text{Nu} = 0.36 \text{Re}_{\text{imp}}^{0.67} \text{Pr}^{0.33} \left(\frac{\mu_b}{\mu_w} \right)^{0.14} \quad (\text{S15})$$

$$\text{Re}_{\text{imp}} = \frac{N_{\text{imp}} D_{\text{imp}}^2 \rho}{\mu_b} \quad (\text{S16})$$

$$\text{Pr} = \frac{Cp \mu_b}{k_{\text{fb}}} \quad (\text{S17})$$

The parameters in Equations S14 through S17 are as follows: Nu is the Nusselt number, k_{fb} is the thermal conductivity of the bulk fluid, D is the tank diameter, Re_{imp} is the impeller Reynolds number, Pr is the Prandtl number, μ_b is the viscosity of the bulk fluid, μ_w is the viscosity of the fluid at the wall, N_{imp} is the rotational speed of the impeller, D_{imp} is the impeller diameter, and ρ is the average density of the fluid, and Cp is the average heat capacity of the fluid.

Thermal conductivity, heat capacity, and density of the fluid was found by mass-weighted average using Equation S10. The diameter of the tank varies depending on the scenario. For the fluid viscosity, μ_b and μ_w are considered equal as there is no known data for viscosity of the fluid at the wall. Since we are considering that the environment will be cooler than the slurry, the viscosity at the wall should be higher than that of the bulk fluid. Theoretically, the relation between the viscosities should be less than one, therefore, considering both as equal is a conservative approach. Apparent viscosity of dairy manure at digester temperature and rate of shear was assumed.

A two-impeller ($N_{\text{impellers}}$) approximation on opposite sides was considered [33, 40]. There is no significant difference in digester performance between mixing intensities of 1 and 25 rpm [42]. Additionally, reducing the mixing time in full-scale CSTR digesters does not affect nutrient distribution during the co-digestion of energy crops and animal manure [43]. Therefore, a mixing speed of 20 rpm is assumed to minimize energy costs. A marine propeller is selected as the impeller type due to its established use in digesters [44]. This type of propeller induces axial flow, which increases mixing efficiency for liquid-solid suspensions, providing good homogenization with low mixing power [41, 45–47].

To calculate the power requirement for the continuous mixing, Equation S18 was used [41].

$$P = N_p \rho N_i^3 D_i^5 \quad (\text{S18})$$

Where P (kW) is the power and N_i is the impeller power number. A summary of the assumed parameters is shown in Table S8.

Table S8 Digester properties and parameters.

Parameter	Value	Units	Reference
<i>Operating conditions</i>			
HRT	22	d	[34]
V _w	70	%	[39]
T _{digester}	37	°C	[33]
T _{air}	14	°C	[15]
h _{air}	10	W/m ² ·°C	[48]
μ _b	0.92	Pa·s	[49]
<i>Mixing and geometric parameters</i>			
D _i	2.50	m	
N _{impellers}	2		[33]
N _i	20	rpm	[42]
N _p	0.35		[41]
<i>Construction layers and insulation properties</i>			
B ₁	10	cm	[39]
B ₂	10	cm	[39]
k ₁	1.50	W/m·°C	[50]
k ₂	0.03	W/m·°C	[51]

S2.2 Biogas utilization

Biogas produced inside the digester follows two possible end-use pathways. The biogas can either enter a CHP unit for electricity production or go through an upgrading process to generate RNG.

S2.2.1 Electricity production

In the electricity production scenario, a CHP unit was used to convert biogas into electricity while recovering thermal energy. The CHP unit was modeled using a simplified gas combustion and energy conversion approach, in which biogas is combusted with air to generate electricity and recover usable heat.

Although farm-scale anaerobic digestion systems typically employ reciprocating engines, the CHP unit was represented as an equivalent thermodynamic system to capture overall electrical efficiency and heat recovery [52, 53].

The recovered thermal energy from the exhaust gases was assumed to be available for process heating and was modeled as steam to meet the digester heat demand.

The model considers biogas and water as inputs and electricity, steam, and exhaust gases as outputs. System performance is characterized by the overall efficiency (η_{Overall}) and electric efficiency (η_{Electric}) of the gas turbine, defined on a high heating value (HHV) basis. The thermal efficiency (η_{Thermal}) corresponds to the recoverable fraction of the total energy as heat (Equation S19).

$$\eta_{\text{Thermal}} = \eta_{\text{Overall}} - \eta_{\text{Electric}} \quad (\text{S19})$$

Combustion of methane (CH_4) follows Equation S20, an exothermal reaction where part of the heat is converted to electricity.



The total energy released by combustion (H_{comb} , MJ h⁻¹) is calculated from the methane mass flow F_{CH_4} in kg h⁻¹ and HHV (Equation S21).

$$H_{\text{comb}} = F_{\text{CH}_4} \cdot HHV \quad (\text{S21})$$

The electric power output (P , kW) is calculated from Equation S22.

$$P = \frac{H_{\text{comb}} \cdot \eta_{\text{Electric}}}{3600} \quad (\text{S22})$$

Steam generation requires heating water from groundwater temperature T_{in} to saturation temperature ($T_{\text{out}} = 100^\circ\text{C}$), plus the latent heat of vaporization. The change in enthalpy (Δh , kJ kg^{-1}) from water to steam is calculated as the sum of sensible heat and phase-change equations adopted from [41]:

$$\Delta h_{\text{sensible}} = Cp(T_{\text{out}} - T_{\text{in}}) \quad (\text{S23})$$

$$\Delta h = \Delta h_{\text{sensible}} + \Delta h_{\text{vap}} \quad (\text{S24})$$

Then, steam production (F_{steam} , kg h^{-1}) is defined by:

$$F_{\text{steam}} = \frac{H_{\text{comb}} \cdot \eta_{\text{Thermal}}}{\Delta h} \quad (\text{S25})$$

Where h_{sensible} is the sensible heat, h_{vap} is the latent heat of vaporization of water at 100°C and 101.3 kPa. See Table S7 for Cp and T_{in} values.

The corresponding water demand (F_{water} , kg h^{-1}) is:

$$F_{\text{water}} = F_{\text{steam}} \quad (\text{S26})$$

Steam produced is transported through a pipe and is used to heat the digester. Energy required (Q_{input}) is calculated by Equation S8, and the amount of steam needed ($F_{\text{steam, digester}}$, kg h^{-1}) is given by:

$$F_{\text{steam, digester}} = \frac{Q_{\text{input}}}{\Delta h} \quad (\text{S27})$$

The Table S9 summarizes the parameters considered for the CHP.

Table S9 CHP properties and parameters.

Parameter	Value	Units	Reference
η_{Overall}^1	68.5	%	[52]
η_{Electric}^1	35.0	%	[52]
η_{Thermal}^2	33.5	%	
HHV	55.5	MJ/kg	[54]
Δh_{vap}	2256.4	kJ/kg	[41]

¹Efficiencies defined on HHV basis.

²Thermal efficiency was manually calculated.

S2.2.2 RNG production

A two-stage membrane separation system was modeled to upgrade biogas into concentrated methane for pipeline injection. The system consists of several steps, including prior compression of the gas, with CO_2 permeating through the membrane while CH_4 is retained. The unit performance is defined by the methane recovery ($CH_{4\text{rec}}$) and product purity ($CH_{4\text{purity}}$) parameters. For most states, the energetic standards require a CH_4 content of at least 95% v/v [55].

Prior to entering the membrane, biogas is cooled and dried to external temperature. Although gas flowrates and equipment sizing are typically reported as volumetric flows ($\text{Nm}^3 \text{h}^{-1}$), BioSTEAM operates on a mass-flow basis. Therefore, volumetric and molar quantities were converted to mass flow using the ideal gas law at normal conditions (0°C and 101.3 kPa).

The volumetric flow of methane, carbon dioxide, and biogas ($V_{\text{in},i}$, $\text{Nm}^3 \text{h}^{-1}$) entering the membrane system are estimated as:

$$V_{\text{in},i} = \frac{n_{\text{in},i} RT}{P} \quad i = \text{CH}_4, \text{CO}_2 \quad (\text{S28})$$

$$V_{\text{biogas}} = V_{\text{CH}_4, \text{in}} + V_{\text{CO}_2, \text{in}} \quad (\text{S29})$$

The molar flow of CH₄, CO₂ and RNG recovered in the product stream by Equations S30-S32.

$$n_{\text{CH}_4, \text{ out}} = n_{\text{CH}_4, \text{ in}} \cdot \text{CH}_{4\text{rec}} \quad (\text{S30})$$

$$n_{\text{RNG}} = \frac{n_{\text{CH}_4, \text{ out}}}{\text{CH}_{4\text{purity}}} \quad (\text{S31})$$

$$n_{\text{CO}_2, \text{ out}} = n_{\text{RNG}} - n_{\text{CH}_4, \text{ out}} \quad (\text{S32})$$

Finally, the mass flowrates (kg h⁻¹) of the product and individual components are obtained from:

$$F_{\text{out}, i} = \frac{n_{\text{out}, i} \cdot M_i}{1000} \quad i = \text{CH}_4, \text{CO}_2 \quad (\text{S33})$$

$$F_{\text{RNG}} = F_{\text{CH}_4, \text{ out}} + F_{\text{CO}_2, \text{ out}} \quad (\text{S34})$$

Power consumption (kW) of the unit is calculated in Equation S35.

$$P = e \cdot V_{\text{biogas}} \quad (\text{S35})$$

Where e is the specific energy consumption of the membrane system. Table S10 shows the properties and parameters considered for the membrane separation system.

Table S10 Membrane separation system properties and parameters.

Parameter	Value	Units	Reference
CH _{4rec}	99	% mol	[56]
CH _{4purity}	98	% mol	[55]
e _{req}	0.35	kWh/Nm ³	[55]
R	8.31	J/mol · K	[57]
M _{CH₄}	16.04	g/mol	[58]
M _{CO₂}	44.01	g/mol	[59]

S2.3 Storage

Storage units are considered in the model for manure and lignocellulosic feedstocks. Dairy farms typically have a lagoon for manure collection through the winter. This lagoon storage will be used for the liquid digestate produced. In addition, a small covered lagoon storage unit is built for manure collection prior to the mixing tank. Solid digestate will be continuously used as bedding, so storage is not considered on the farm.

S2.3.1 Manure storage

A storage lagoon is used to store dairy manure prior to the mixing tank. The lagoon volume (V_{lagoon} , m³) is calculated given the solid (V_{sludge}) and liquid (V_{liquid}) volume fraction of the manure through Equations S36 to S38.

$$V_{\text{sludge}} = r_{\text{sludge}}(F_{\text{manure}} \cdot x_{\text{solids}} \cdot \tau_{\text{manure}}) \quad (\text{S36})$$

$$V_{\text{liquid}} = \frac{F_{\text{manure}} \cdot x_{\text{moisture}} \cdot \tau_{\text{manure}}}{\rho_{\text{manure}}} \quad (\text{S37})$$

$$V_{\text{lagoon}} = V_{\text{sludge}} + V_{\text{liquid}} \quad (\text{S38})$$

Where r_{sludge} is the sludge accumulation for dairy cattle, F_{manure} is the manure flow entering the lagoon, x_{solids} and x_{moisture} are the solids and moisture fractions, and τ_{manure} is the retention time. These equations

were adapted from the lagoon methodology presented by EPA [3]. Manure composition and density are reported in Tables S1 and S2, respectively.

The lagoon geometry was defined following the design criteria established by EPA [3], assuming a trapezoidal prism configuration. The maximum lagoon depth (h_{lagoon}) was obtained by adding the design freeboard ($h_{\text{freeboard}}$) to the initial depth (h_{initial}). The soil factor (f_{soil}) accounts for soil volume changes during excavation. The total volume excavated was given by $V_{\text{excavated}}$. The top width (w_2) and lagoon length (L) were determined from the side slope ratio (s) and bottom width (w_1), as shown in Equations S41-S42. Finally, the total surface area to be covered (A_{covered}) was determined using Equation S43 to ensure that biogas generated during storage is contained.

$$h_{\text{lagoon}} = h_{\text{initial}} \cdot (1 + h_{\text{freeboard}}) \quad (\text{S39})$$

$$V_{\text{excavated}} = V_{\text{lagoon}} \cdot (1 + f_{\text{soil}}) \quad (\text{S40})$$

$$w_2 = w_1 + 2 s h_{\text{lagoon}} \quad (\text{S41})$$

$$L = \frac{2V_{\text{excavated}}}{h_{\text{lagoon}}(w_1 + w_2)} \quad (\text{S42})$$

$$A_{\text{covered}} = w_2 \cdot L \quad (\text{S43})$$

Table S11 reflects the properties and design parameters used in the model.

Table S11 Lagoon storage properties and parameters.

Parameter	Value	Units	Reference
τ_{manure}^1	15	d	
r_{sludge}	0.004	m ³ /kg	[3]
h_{initial}	3.0	m	[3]
$f_{\text{freeboard}}$	0.10		[3]
f_{soil}	0.05		[3]
s^2	3		
w_{bottom}^2	10.0	m	

¹Defined based on operational days of the system, accounting for maintenance periods where the digester is not working.

²Assumed based on typical values used in lagoon designs.

S2.3.2 Lignocellulosic feedstocks storage

The storage system was modeled to determine the area requirements to house the lignocellulosic feedstock prior to digestion, accounting for bale dimensions, density, and stacking configuration. For both scenarios, a pole barn structure was used.

On-farm scenario

For the on-farm scenario, biomass is assumed to be stored using a plastic tarp on the side of the farm for a maximum of eleven months, while one month of feedstock is stored inside the pole barn to reduce storage losses [60]. Grasses were assumed to be collected in large square bales for stacking purposes, with dimensions of $h=3$, $w=4$, $l=8$ ft [61–63]. Bale dimensions were converted to meters before performing calculations.

For each feedstock i , the number of bales produced annually ($B_{\text{ann},i}$) was calculated from its total mass ($F_{\text{ann},i}$), bale density ($\rho_{\text{bale},i}$), and bale volume (see Equation S44). The required barn area for one month

of storage ($A_{\text{barn},i}$) was determined using Equation S45, accounting for number of bales stacked (N_{stack}), period of storage in a year (τ_{grass}), and maneuvering space (f_{extra}). The plastic tarp area was calculated by Equation S46, which accounts for the months of outdoors storage (t_{outdoor}).

$$B_{\text{ann},i} = \frac{F_{\text{ann},i}}{\rho_{\text{bale},i} h w l} \quad i = \text{CORN, SWG, WR} \quad (\text{S44})$$

$$A_{\text{barn},i} = \frac{B_{\text{ann},i} w l (1 + f_{\text{extra}})}{\tau_{\text{grass}} N_{\text{stack}}} \quad (\text{S45})$$

$$A_{\text{tarp},i} = t_{\text{outdoor}} \frac{B_{\text{ann},i} w l (1 + f_{\text{extra}})}{\tau_{\text{grass}} N_{\text{stack}}} \quad (\text{S46})$$

Table S12 summarizes the parameters and results for the on-farm storage scenario.

Table S12 Parameters and results for lignocellulosic feedstock storage in on-farm scenario.

Parameter ¹	Corn stover	Switchgrass	Winter rye	Units
$\rho_{\text{bale},i}$ ²	164	175	169	kg/m ³
$B_{\text{ann},i}$	4,698	10,848	10,757	bale/yr
Pole barn				
N_{stack}	3	3	3	bale
f_{extra}	0.2	0.2	0.2	
τ_{grass}	12	12	12	
$A_{\text{barn},i}$	465	768	563	m ²
Plastic tarp				
t_{outdoor}	11	11	11	month
N_{stack}	6	6	6	bale
f_{extra}	0.1	0.1	0.1	
τ_{grass}	12	12	12	
$A_{\text{tarp},i}$	2,347	3,870	2,841	m ²

¹ N_{stack} was assumed based on typical values [60]. f_{extra} was assumed to account for maneuverability and sufficient coverage area. $B_{\text{ann},i}$ and $A_{\text{barn},i}$ were calculated using Equations S44 and S45.

²Bale density values for corn stover and switchgrass were obtained from [64] and [65], respectively. The value for winter rye was estimated as the average of these two.

Purchased scenario

Transportation of the biomass is excluded from the system boundaries, and included in the assumed purchased price. Purchase biomass is assumed to be delivered to the farm and stored on-site for short-term use. A storage capacity for 15 days was assumed, representing a moderate value between long-term on-farm storage and continuous biorefinery operation [66]. This period provides sufficient capacity without extensive infrastructure investment.

Grasses were assumed to be collected and transported in large square bales with the same dimensions defined previously. For each feedstock i , Equation S44 was used to determine the number of bales delivered annually, and Equation S45 was used to calculate the pole barn area for the amount (24) of 15 day periods in a year.

Table S13 summarizes the parameters and calculated storage areas for the purchased scenario.

S2.4 Pre- and post-processing

Handling operations are carried out both prior to and after anaerobic digestion. Pre-processing improves feedstock characteristics for digestion, while post-processing enables digestate management. Lignocellulosic

Table S13 Parameters and results for lignocellulosic feedstock storage in purchased scenario.

Parameter ¹	Corn stover	Switchgrass	Winter rye	Units
$\rho_{\text{bale},i}$ ²	164	175	169	kg/m ³
$B_{\text{ann},i}$	23,100	21,650	22,350	bale/yr
Pole barn				
N_{stack}	3	3	3	bale
f_{extra}	0.2	0.2	0.2	
τ_{grass}	24	24	24	
$A_{\text{barn},i}$	2,287	2,143	2,212	m ²

¹ N_{stack} was assumed based on typical values [60]. f_{extra} was assumed to account for maneuverability and sufficient coverage area. $B_{\text{ann},i}$ and $A_{\text{barn},i}$ were calculated using Equations S44 and S45.

²Bale density values for corn stover and switchgrass were obtained from [64] and [65], respectively. The value for winter rye was estimated as the average of these two.

biomass is shredded to reduce particle size before the mixing tank, and digestate is processed through a solid-liquid separator to recover the fractions.

S2.4.1 Shredder

Pre-processing of raw lignocellulosic biomass is recommended to increase surface area and enhance microbial accessibility, which improves the methane yield [67–69]. A hammermill shredder was modeled, operating at a particle size of 12 mm [70]. The power requirement (P) was calculated as a function of the incoming feedstock flowrate ($F_{\text{in},i}$, Mg h⁻¹) and the specific energy consumption (e), as given by Equation S47.

$$P = F_{\text{in},i} e \quad (\text{S47})$$

A specific energy consumption of 22.14 kWh Mg⁻¹ was adopted [70].

S2.4.2 Mixing tank

The mixing tank was modeled to homogenize the feedstocks (dairy manure, lignocellulosic biomass, water, and recirculated slurry) before entering the digester. The tank operates with a working volume of 80% and a retention time of one hour. The geometry is assumed cylindrical with a height-to-diameter ratio of 1.5. The target total solids (TS) content entering the digester was fixed at 10% (see Section S1 for more detail).

For recirculation, the water requirement was calculated dynamically within the mixing tank unit to account for the additional solids introduced by the recirculated digestate. In this case, the tank determines the total dry matter ($W_{\text{d.m.}}$) from all the inlet streams i and computes the required water flow (F_{water}) to achieve the specified TS (TS_{target}) content according to Equations S48 and S49:

$$W_{\text{slurry}} = \frac{W_{\text{d.m.}}}{TS_{\text{target}}} \quad (\text{S48})$$

$$F_{\text{water}} = W_{\text{slurry}} - \sum_i F_i \quad i = \text{manure, grass, recirculated slurry} \quad (\text{S49})$$

The resulting mixture outlet was verified to meet the desired TS target. The overall temperature and heat capacity of the slurry was calculated using Equation S10.

The power consumption for mixing is estimated using Equation S18 [41]. A marine propeller operating at 150 rpm is assumed, with an impeller diameter equal to half the tank diameter. The tank and impeller dimensions are automatically scaled the total volumetric flow of the inputs for each scenario.

S2.4.3 Solid-liquid separator

After anaerobic digestion, the slurry (digestate) was processed through a solid-liquid separator. The residual nutrients in the digestate can still produce methane emissions, and solid-liquid separation after anaerobic digestion can mitigate up to 68% of emissions compared to raw manure [71]. Although most of California dairies use a solid-liquid separation technology, as of 2013 less than 20% of U.S. dairy farms used a manure separator [40].

In this study, the separator was included to recover solids for animal bedding and liquid effluent for land application. The equipment capacity was set equal to the digestate inflow rate, and separation performance assumed a moisture content of 60% (w.b.) in the solid fraction and a solids capture efficiency of 99.7% [72]. The solid-liquid separation unit was modeled using BioSTEAM’s built-in *Splitter* class. The liquid fraction retained the remaining water and solids. No additional mass balance equations were solved as the splitting is handled internally.

S2.5 Auxiliary units

Auxiliary units were included in the model to support process operations such as hydrogen sulfide removal, heating, compression, pumping, and recirculation. These units ensure proper reactor conditions and product handling across scenarios.

S2.5.1 Hydrogen sulfide removal

Hydrogen sulfide (H_2S) is commonly present in raw biogas. Its removal is required to prevent corrosion, protect equipment, and comply with pipeline specifications. In this study, H_2S removal is modeled using micro-aeration process, in which limited supply of oxygen is injected into the digester for sulfide oxidation [73–75].

A custom BioSTEAM unit operation was implemented to account for the oxygen injection. The required unit dimensions were determined based on the volumetric flow of biogas entering the treatment under normal conditions (0°C , 101.3 kPa). The volumetric flow of each gas component (CH_4 , CO_2 , H_2O) was calculated using Equations S28-S29.

S2.5.2 Heat exchanger

Slurry

A heat exchanger was modeled within the digester to maintain the slurry at mesophilic temperature. The unit was simulated using BioSTEAM’s built-in *HXutility*, which transfers heat to the process through a thermal utility.

In the electricity production scenario, the recovered heat from the CHP unit supplies the thermal energy required for digester heating. If the recovered heat were insufficient, additional steam would be purchased to meet the demand. However, in all simulated cases, CHP heat recovery fully satisfied the heating requirement.

In the RNG production scenario, steam is generated by a dedicated boiler and used to supply the required digester heat duty.

The heat demand of the slurry was determined from the general energy balance (Equation S8), and the required steam flow was automatically computed within BioSTEAM to satisfy this duty.

Dehydration

Raw biogas exiting the digester contains trace amounts of water vapor. Warm biogas leaving the digester at mesophilic temperature cools to ambient temperature while flowing through the pipeline, and water vapor condenses. To account for this, BioSTEAM’s built-in *HXutility* was used to simulate the temperature drop of the biogas stream, followed by a *Splitter* unit representing a water trap, where condensed water is fully removed [73].

S2.5.3 Compressor

In the RNG production scenario, the upgraded gas must be compressed before injection into the natural gas grid. Pipeline specifications vary by system type: transmission pipelines operate above 6.90 MPa, while distribution pipelines supply homes and businesses at pressures between 70-1,380 kPa [76]. Anaerobic digestion RNG can be injected into either pipeline [77]. For this study, compression to 1,380 kPa was selected to represent farm production with distribution pipeline injection.

An isentropic compressor was modeled in BioSTEAM to achieve the required outlet pressure (p_2). The inlet molar flowrate of RNG, n_{RNG} , was taken from Equation S31. The specific compression work (W_{isen} , W) was estimated using the ideal-gas isentropic compression equation [78]:

$$W_{\text{isen}} = \frac{k}{k-1} \frac{n_{\text{RNG}} R T_{\text{in}}}{3600} \left[\left(\frac{p_2}{p_1} \right)^{(k-1)/k} - 1 \right] \quad (\text{S50})$$

Where R is the ideal gas constant, T_{in} is the inlet temperature, p_1 and p_2 are the inlet and outlet pressures, and k is the isentropic exponent defined as:

$$k = \frac{C_p}{C_v} \quad C_v = C_p - R \quad (\text{S51})$$

The real compressor power requirement (P , kW) accounts for the compressor isentropic efficiency (η):

$$P = \frac{W_{\text{isen}}}{\eta} \quad (\text{S52})$$

Table S14 summarizes the parameters considered for the compressor.

Table S14 Compressor properties and parameters.

Parameter	Value	Units	Reference
p_1 ¹	400	kPa	[79]
p_2	1,380	kPa	[76]
T_{in} ²	14	°C	[15]
C_p	35.7	J/mol · K	[58]
η	80.0	%	[80]

¹Adopted from [79] as the membrane separation outlet pressure.

²Assumed as external temperature.

S2.5.4 Pump

Pumps were modeled using BioSTEAM's built-in *Pump* unit, which changes the outlet pressure. Power demand was estimated using the default correlations adopted by BioSTEAM [81, 82].

Two pumping operations were included in the model. 1) A pump conveys dairy manure from the manure storage lagoon to the mixing tank. 2) For recirculation, a second pump returns liquid digestate from the solid-liquid separator to the mixing tank.

S2.5.5 Boiler

In the RNG production scenario, a boiler supplies the thermal energy required to heat the digester. The boiler was created using BioSTEAM's built-in *Facility* class, which runs after the main mass and energy balances are solved. This allows the digester heat requirement (Q_{input} , kJ h⁻¹) to be calculated first.

The boiler was customized to operate on natural gas and generate low-pressure steam. The system performance is defined by a boiler efficiency (η_{boiler}) of 95%, defined on high heating value (HHV) basis [83]. Combustion of methane follows Equation S20. The total heat needed to be released by fuel combustion is:

$$H_{\text{comb}} = \frac{Q_{\text{input}}}{\eta_{\text{boiler}}} \quad (\text{S53})$$

The required natural gas mass flowrate is then:

$$F_{\text{nat gas}} = \frac{H_{\text{comb}}}{HHV} \quad (\text{S54})$$

The change in enthalpy (Δh) from water to steam is calculated as the sum of sensible heating and phase-change using Equations S23-S24. The steam flowrate (F_{steam} , kg kJ h^{-1}) required for digester heating is:

$$F_{\text{steam}} = \frac{Q_{\text{input}}}{\Delta h} \quad (\text{S55})$$

The corresponding water demand is defined in Equation S26. Properties and parameters are summarized in Tables S7 and S9.

S2.5.6 Recirculation

Lignocellulosic feedstocks contain recalcitrant molecules that limit the complete degradation of biomass and biogas conversion. Consequently, a fraction of biodegradable material remains in the digestate. Recirculating part of the liquid digestate back to the digester has been reported to improve biogas production, enhance microbial activity, and reduce water and heat requirements for CSTR operation [84–86].

In this study, a recirculation ratio of 50% was adopted based on values commonly reported in literature [87, 88]. Recirculation was modeled with BioSTEAM’s built-in *Splitter* class, which divides the liquid digestate stream into two outlet streams according to the specified ratio. One portion is returned to the mixing tank, while the remaining flow is sent to the digestate storage lagoon.

S3 Techno-Economic Model

The economic evaluation was performed using BioSTEAM’s *TEA* class, which conducts a discounted cash-flow analysis based on the system configuration and user-defined financial assumptions.

A discount rate of 8% was selected (defined as IRR in BioSTEAM), consistent with values reported for investments in concentrated animal feeding operations and anaerobic digestion systems [89–91]. The project was assumed to be small-scale, requiring a 2-year construction period [78, 92]. Fixed capital investments were distributed in the first year (FCI year 1) and second year (FCI year 2).

Depreciation followed the IRS Modified Accelerated Cost Recovery System (MACRS) [90, 92]. The system was assumed to operate 95% of the year, allowing downtime for maintenance periods of the CHP and membrane separation units. The digester was assumed to operate continuously.

Income tax was modeled as total effective tax rate including federal and Pennsylvania corporate income tax [93]. Working capital (WC) was assumed as a fraction of fixed-capital investment following BioSTEAM convention.

Table S15 summarizes the financial parameters used in the TEA.

Table S15 Financial and operational parameters used in the TEA.

Parameter	Value	Units	Reference
Discount rate	8	%	[90]
Starting year ¹	2025	year	
Project lifetime	20	years	[91, 93]
Depreciation period	7	years	[90]
Income tax	40	%	[93]
Operating days	347	days/year	[93]
CI year 1	40	% of FCI	
CI year 2	60	% of FCI	
WC	5	% of FCI	[92]

¹The starting year corresponds to the year of analysis.

S3.1 Capital costs

Capital costs (CAPEX) were divided into direct and indirect costs in accordance with standard TEA methodology [94]. Total capital cost is calculated as:

$$C_{\text{CAPEX}} = FCI + WC \quad (\text{S56})$$

$$FCI = C_{\text{direct}} + C_{\text{indirect}} \quad (\text{S57})$$

Direct costs

Capital costs in this study include both direct and indirect costs and were estimated as a function of purchased equipment cost (PEC).

S3.1.1 Purchased equipment cost

Each unit operation described in Section S2 has an associated equipment item. Baseline equipment costs were obtained from literature and vendor databases and were scaled to the required process capacity using the six-tenths rule [94]. Scaled purchase costs were further adjusted to 2024 U.S. dollars using the Chemical Engineering Plant Cost Index (CEPCI). The purchase cost of each equipment item was calculated using:

$$C_{\text{purchase}} = C_{\text{baseline}} \left(\frac{S_{\text{model}}}{S_{\text{baseline}}} \right)^{\text{exp}} \left(\frac{CEPCI_{2024}}{CEPCI_{\text{baseline}}} \right) \quad (\text{S58})$$

Where C_{purchase} is the purchase cost adjusted to 2024, C_{baseline} is the reported cost in baseline year, S_{model} and S_{baseline} are the required and reported capacity associated with the model and baseline cost respectively. The scaling exponent used is defined by exp .

The purchased equipment price after scaling depends on the scenario evaluated. Table S16 lists the baseline parameters used for equipment cost scaling.

Note: Manure and lignocellulosic biomass storage do not follow the six-tenths rule because their costs depend on construction materials or civil engineering work rather than equipment capacity. For these units, capital cost was estimated using direct construction and unit cost [3, 95–97].

Table S16 Baseline equipment cost parameters.

Equipment	S_{baseline}	Units	exp	C_{baseline}^1	Baseline year	Reference
Digester	31	MMgal ²	0.6	\$6,750,000	2010	[92]
CHP	5,240	kW	0.6	\$4,111,200	2014	[98]
Mixing tank	264,116	kg/h	0.7	\$203,000	2009	[92]
Mixing tank agitator	264,116	kg/h	0.5	\$90,000	2009	[92]
Shredder	10	Mg/h	0.6	\$795,000	2020	[70]
Dehydration	1	Unit		\$9,026	2025	[99]
Solid-liquid separator	5,520	kg/h	0.6	\$275,000	2005	[70]
Membrane separation	500	Nm ³ /h	0.6	\$985,000	2017	[55]
Boiler	0.5	Mg/h	0.6	\$10,000	2024	[100]
Compressor	10	hp	0.6	\$9,099	2024	[101]

¹Costs shown before CEPCI adjustment.

²MMgal = Million gallons.

S3.1.2 Direct and indirect capital costs

Direct cost factors

Direct and indirect costs are expressed as fractions of the PEC [92, 94]. The scope of this project was on a farm scale and capital cost estimation is usually done for a plant scale. Then, a custom direct cost application was performed for each equipment to represent the actual needs. See Table S17 for details.

Direct costs include installation, instrumentation, piping, electrical work, buildings, and yard improvements. Service facilities were assumed to be already available on the dairy farm, so no additional facilities were added.

Two different building cost fractions were used in this study to realistically represent the type of structure required for each unit operation. For low-cost equipment (e.g., shredder, mixing tank, compressor, boiler), the general building factor of 15% of PEC was applied. This fraction represents the cost of a simple enclosed structure and is consistent with standard assumptions [94]. For high-cost equipment such as the CHP unit and membrane separation system, a reduced building factor of 7% of PEC was applied to avoid overestimating capital costs. These units are typically installed in low-cost prefabricated insulated and reinforced buildings.

Indirect cost factors

Indirect costs include engineering, construction, legal expenses, contractor fees, and contingency. These were also estimated as percentages of PEC.

Table S18 summarizes the cost fractions used in this study.

S3.1.3 Pipeline injection

In the RNG scenario, connection to the natural gas grid was included as a one-time capital cost. The total pipeline cost (C_{pipeline}) was estimated following [55]:

Table S17 Capital cost factors considered for each equipment.

Capital Cost	Installation	Instrumentation	Piping	Electrical	Building	Yard improvement	Indirect costs ¹
Manure pit		●	●			●	●
Grass storage	●					●	●
Shredder	●			●	●	●	●
Mixing tank	●		●	●	●	●	●
Digester		●	●	●		●	●
Dehydration	●		●				●
Solid-liquid separator	●		●	●		●	●
CHP	●	●	●	●	●	●	●
Membrane separation	●	●	●	●	●	●	●
Boiler	●	●	●	●	●	●	●
Compressor	●	●	●	●	●	●	●

A green dot (●) indicates equipment included in both the electricity and RNG scenarios, blue dot (●) indicates equipment included only in the electricity scenario, and a yellow dot (●) indicates equipment included only in the RNG scenario.

¹ All indirect cost categories are applied to each equipment item.

Table S18 Direct and indirect cost factors.

Item	% of PEC
Direct costs	
Purchased equipment	100
Installation	30
Instrumentation	15
Piping	15
Electrical	10
Building (general) ¹	15
Building (reduced) ²	7
Yard improvement	5
Service facility	0
Indirect costs	
Engineering	20
Construction	30
Legal expenses	2
Contractor fees	15
Contingency	15

¹Building (general) was applied to low-cost equipment.

²Building (reduced) was used for high-cost units (CHP and membrane separation) to avoid overestimating building cost.

$$C_{\text{pipeline}} = C_{\text{material}} d + C_{\text{inter}} + C_{\text{eng}} + C_{\text{monitor}} \quad (\text{S59})$$

Where C_{material} is the cost of the pipeline material per distance, d is the assumed distance between the farm and the nearest pipeline injection point, and C_{inter} , C_{eng} , and C_{monitor} represent the interconnection fee, engineering cost, and gas monitoring equipment cost, respectively.

A baseline pipeline distance of 2 km was assumed [55]. Table S19 summarizes all input parameters.

Table S19 Pipeline injection cost parameters.

Parameter	Value	Units
C_{material}	625,000	\$/km
C_{inter}	560,000	\$
C_{eng}	200,000	\$
C_{monitor}	250,000	\$
d	2	km

All values from [55].

S3.2 Operating costs

Operating costs (OPEX) were divided into fixed and variable operating costs [94]. Total annual operating cost is:

$$C_{\text{OPEX}} = C_{\text{variable}} + C_{\text{fixed}} \quad (\text{S60})$$

S3.2.1 Fixed operating costs

Fixed operating costs include property insurance, maintenance, and administration, which were modeled as a fraction of the FCI. No property taxes were included because anaerobic digestion systems are generally treated as agricultural facility [93].

For anaerobic digestion plants, operation and maintenance costs have common value around 2% of FCI [55, 89, 91, 92]. Labor and maintenance were treated separately; maintenance was assumed 1.8% of FCI, with unit-specific maintenance added individually. On-farm digesters are typically operated by the farmer [73]. The model assumes 6 hours of operator attention per day, consistent with [89]. The annual labor cost was calculated as:

$$C_{\text{labor}} = h_{\text{annual}} \cdot w \quad (\text{S61})$$

Where h_{annual} is the annual labor hours and w is the operator wage (\$19.07 h⁻¹) [102].

Property insurance was taken as 0.4 % of FCI [92]. Supplies were assumed at \$500 year⁻¹ [93]. Administration for RNG scenario was modeled as 0.9 % of FCI.

S3.2.2 Variable operating costs

Variable operating costs include utilities, consumables, and feedstock purchases that scale with the mass flowrates processed or energy generated. Table S20 summarizes the prices used.

- **Electricity consumption:** Electricity consumption was calculated from the power requirements of each unit operation. Power (P , kW) was calculated for the digester, mixing tank, shredder, CHP unit, membrane separation, compressor (see Section S2 for detail). Electricity demand of the solid-liquid separator was estimated as 2% of its PEC [3]. Pumping electricity was estimated using BioSTEAM's built-in power correlations. Annual consumption and cost were computed using BioSTEAM's *TEA* class.
- **Heat and steam requirements:** Heat requirements for the digester slurry were calculated using the energy balance in Section S2.
 - **Electricity scenario:** steam is provided entirely by the CHP unit, no additional purchase was required.
 - **RNG scenario:** steam is generated by a boiler using natural gas. Natural gas consumption was calculated using Equation S54.
- **Water use:** Water consumption was obtained from the mixing tank calculations in Section S2.
- **Feedstocks:** Dairy manure was given a value of \$ 0, as the liquid digestate is ultimately land-applied similarly to manure in farms without AD systems. Lignocellulosic feedstock costs depend on scenario:
 - **On-farm scenario:** cost of planting and harvesting.
 - **Purchased scenario:** market price including delivery to the farm.
- **Consumables:**
 - Oxygen for microaeration H₂S removal [75].
 - Membrane replacement of \$20,000 every 5 years (annualized as \$4,000 year⁻¹) [55].
 - Annual lagoon operation and maintenance costs were assumed as 5% of its PEC [3].

S3.2.3 Revenues

Revenues were calculated based on the products generated in each scenario. Table S21 lists the prices considered.

- **Electricity:** In the electricity scenario, annual electricity revenue is calculated from the electricity produced (P , kWh):

$$C_{\text{elec}} = P_{\text{annual}} \cdot p_{\text{elec}} \quad (\text{S62})$$

where p_{elec} is the selling price. Because the system could offset on-farm electricity use first and exports the excess, the residential electricity rate was used [103].

Table S20 Variable operating costs.

Parameter	Value	Units	Reference
Electricity	0.17	\$/kWh	[103]
Natural gas	4.29	\$/Mcf ¹	[104]
Water	0.78	\$/m ³	[105]
Oxygen	0.0025	\$/m ³ of biogas	[75]
Membrane replacement	4,000	\$/year	[55]
Feedstocks			
Dairy manure	0		
on-farm scenario			
Corn stover	18	\$/d.m. Mg	[106]
Switchgrass	32	\$/d.m. Mg	[65]
Winter rye	55	\$/d.m. Mg	[107]
Purchased scenario			
Corn stover	78	\$/d.m. Mg	[108]
Switchgrass	90	\$/d.m. Mg	[109]
Winter rye	121	\$/d.m. Mg	[110]

¹Mcf = thousand cubic feet.

- **Renewable natural gas:**

In the RNG scenario, pipeline-quality gas is injected into the gas grid. RNG from dairy manure and lignocellulosic biomass used qualifies as a D3 cellulosic biofuel under the Renewable Fuel Standard (RFS) and generates Renewable Identification Numbers (RINs) [111]. Total RNG revenue selling price was calculated as:

$$C_{\text{RNG}} = F_{\text{RNG}} \cdot (p_{\text{nat gas}} + p_{\text{RIN}}) \quad (\text{S63})$$

Where F_{RNG} is the RNG flowrate (kg h⁻¹) calculated in Section S2. Natural gas and RIN prices ($p_{\text{nat gas}}$, p_{RIN}) were converted to \$ kg⁻¹CH₄ to match BioSTEAM's default product basis.

- **Solid digestate:** Liquid digestate was assumed to be land-applied without changing original manure application practices; therefore, no revenue is generated. However, solid digestate can be used as bedding, reducing bedding purchases. The value of the solids was calculated as:

$$C_{\text{solids}} = F_{\text{solids}} \cdot p_{\text{bedding}} \quad (\text{S64})$$

Table S21 Product prices.

Parameter	Value	Units	Reference
p_{elec} ¹	0.17	\$/kWh	[103]
$p_{\text{nat gas}}$ ²	0.20	\$/kg	[104]
p_{RIN} ³	1.86	\$/kg	[112]
p_{bedding}	35.25	\$/Mg	[113]

¹Electricity price was calculated as the median value over 2022-2024.

²Natural gas price was calculated as the median value over 2019-2024.

³RIN price was calculated as the median value over 2021-2024.

S3.2.4 Financial incentives

A capital grant or equivalent financial support mechanism was included as a financial incentive for both electricity and RNG systems. Financial support amount (grant) was modeled as a percentage of the fixed capital investment:

$$C_{\text{grant}} = FCI \cdot f_{\text{grant}} \quad (\text{S65})$$

Where f_{grant} is the grant fraction (0-1). The base case scenario assumes no grant. Grants were applied after all direct and indirect capital costs were calculated.

S3.2.5 Economic indicators

Two economic indicators were used to evaluate project feasibility: Net Present Value (NPV) and Internal Rate of Return (IRR). Both were obtained directly using BioSTEAM's built-in *TEA* class.

NPV was calculated over the 20-year project lifetime and IRR was found for an NPV=0.

S4 Sensitivity and Uncertainty Analysis

A sensitivity and uncertainty analysis was performed to evaluate how variations in key techno-economic parameters influence the financial performance of the AD system.

S4.1 Sensitivity analysis

A local sensitivity analysis was conducted to identify which parameters affect system profitability. For each parameter, a minimum and maximum value was selected from literature, and the model was recalculated while varying only one parameter at a time.

For each scenario (electricity, RNG, on-farm grown biomass, purchased biomass) the full process simulation, including mass balances, energy balances, and TEA was rerun.

Tables S22 and S23 list all parameters evaluated and the assumptions.

Table S22 List of parameters included in sensitivity and uncertainty analysis.

Parameter	Min	Base	Max	Units	Reference
Operating conditions					
Total solids digester	8	10	12	%	[40, 73]
HRT	15	22	30	d	[33, 34, 40]
η_{Overall}	66	68	71	%	[52]
η_{Electric}	24	35	36	%	[52]
Operating days	336	347	357	days/year	[93]
d to pipeline	1	2	3	km	[55]
Prices					
Electricity	0.14	0.17	0.19	\$/kWh	[103]
Natural gas	3.05	4.29	12.10	\$/Mcf	[104]
RIN	1.50	2.97	3.50	\$/RIN	[112]
Solid digestate	28.20	35.25	42.30	\$/Mg	[113]
Dairy manure					
f_{lact}	77	85	86	%	[1, 2]
Water content	13	15	23	% w.b.	[4, 114, 115]
Volatile solids	9.1	10.3	16.3	% w.b.	[4, 114, 115]
Total Carbon	5.0	6.0	6.1	% w.b.	[4, 115]
Total Nitrogen	0.5	0.6	0.7	% w.b.	[4, 115]
Methane yield	95	134	166	mL CH ₄ /g VS	[116, 117]
Corn stover					
Water content	3.0	5.2	7.8	% w.b.	[10, 118, 119]
Volatile solids	87.5	88.0	92.6	% w.b.	[10, 118, 119]
Total Carbon	42.6	43.6	43.6	% w.b.	[10, 118, 119]
Total Nitrogen	0.5	0.6	0.6	% w.b.	[10, 118, 119]
Y	11.2	11.7	11.8	d.m. Mg/ha	[23, 120]
Methane yield	119	169	240	mL CH ₄ /g VS	[118, 121–132]
$p_{\text{on-farm}}$	13	18	27	\$/d.m. Mg	[106, 133]
$p_{\text{purchased}}$	67	79	100	\$/d.m. Mg	[108, 134]

S4.2 Uncertainty analysis

A Monte Carlo analysis with 10,000 iterations was performed for each scenario to quantify the combined effect of all uncertain parameters. In each iteration, random values were generated from defined probability distributions (PERT, triangular, lognormal, empirical). Most parameters were sampled using PERT distributions from the values listed in Tables S22 and S23. Exceptions include the methane yields of lignocellulosic feedstocks, electricity price, natural gas price, and RIN credit, for which distributions were fitted to collected data (Figures S4-S9). The full model was recalculated including mass balances, energy balances, and TEA.

The outputs recorded for each iteration were FCI, NPV, IRR, minimum selling price (MSP) electricity or RNG, and minimum grant percentage to achieve NPV=0.

Table S23 Continue of list of parameters included in sensitivity and uncertainty analysis.

Parameter	Min	Base	Max	Units	Reference
Switchgrass					
Water content	9.7	15.0	19.0	% w.b.	[12, 65]
Volatile solids	77.5	78.0	82.6	% w.b.	[11, 114]
Total Carbon	46.5	46.93	47.3	% w.b.	[12]
Total Nitrogen	0.4	0.5	0.6	% w.b.	[12]
Y	11.2	15.7	18.5	d.m. Mg/ha	[11, 24]
Methane yield	100	140	195	mL CH ₄ /g VS	[114, 135–140]
$p_{\text{on-farm}}$	28	32	45	\$/d.m. Mg	[65]
$p_{\text{purchased}}$	73	90	110	\$/d.m. Mg	[65, 109]
Winter rye					
Water content	2.0	4.1	13.8	% w.b.	[13]
Volatile solids	84.5	88.5	91.6	% w.b.	[13]
Total Carbon	25	37	46	% w.b.	[14, 141]
Total Nitrogen	1	1	1	% w.b.	[14, 141]
Y	6.1	9.0	11.9	d.m. Mg/ha	[25]
Methane yield	127	249	349	mL CH ₄ /g VS	[13, 142–150]
$p_{\text{on-farm}}$	53	55	57	\$/d.m. Mg	[107]
$p_{\text{purchased}}$	110	121	132	\$/d.m. Mg	[110]
Temperature					
$T_{\text{air}}, T_{\text{in, grass}}$ ¹	10	14	18	°C	[15]
$T_{\text{in, manure}}$	14	20	26	°C	[6]
$T_{\text{in, water}}$	7	10	13	°C	[36]

¹ $T_{\text{in, grass}}$ was assumed to be the same as external temperature.

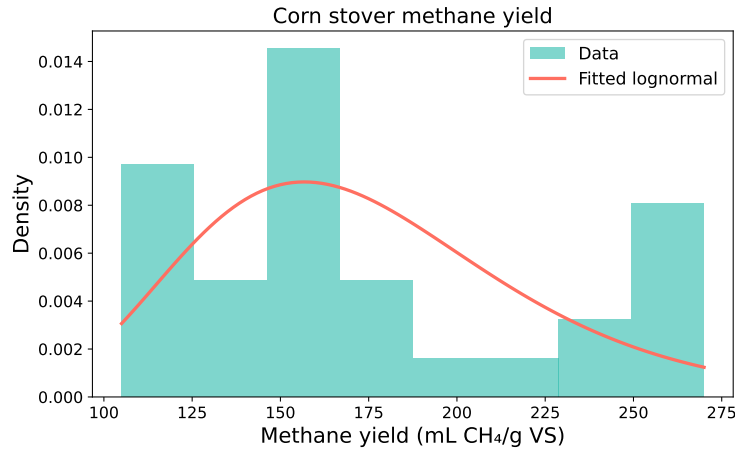


Fig. S4 Methane yield distribution of corn stover [118, 121–132].

Methane yield distributions were fitted directly to the compiled data. A lognormal distribution was applied to corn stover and switchgrass, while winter rye was best represented by a triangular distribution (Figures S4-S6).

Electricity, natural gas, and RIN credit price data were obtained for the years 2022-2024, 2019-2024, 2021-2024, respectively (Figures S7-S9). Beta distributions were fitted to the electricity and RIN credit datasets, while a lognormal distribution was fitted to the natural gas price data.

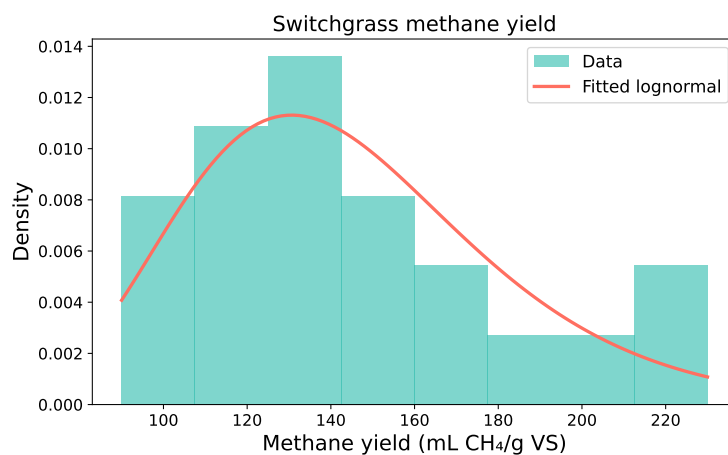


Fig. S5 Methane yield distribution of switchgrass [114, 135–140].

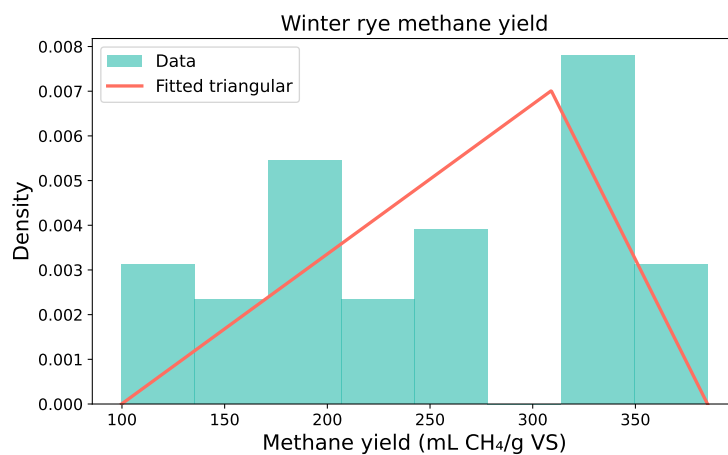


Fig. S6 Methane yield distribution of winter rye [13, 142–150].

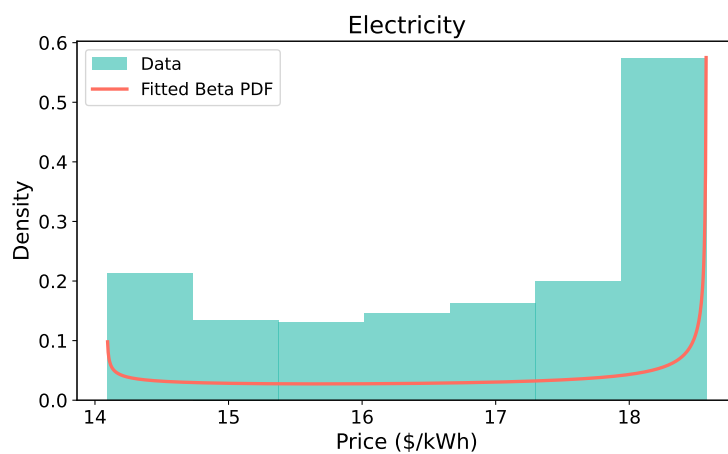


Fig. S7 Price distributions of electricity [103].

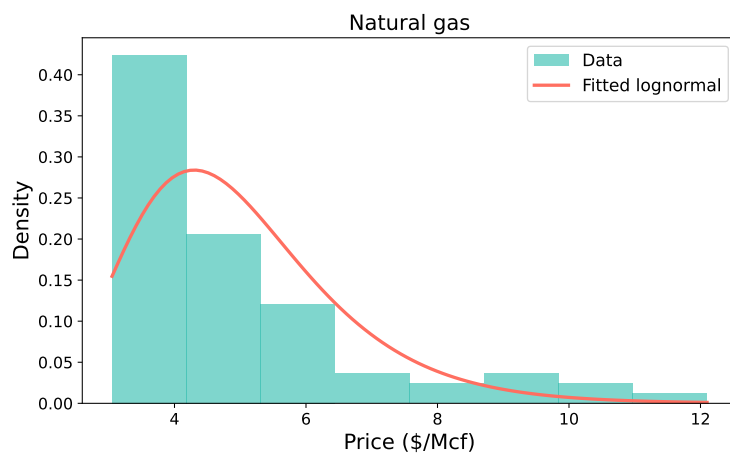


Fig. S8 Price distributions of natural gas [104].

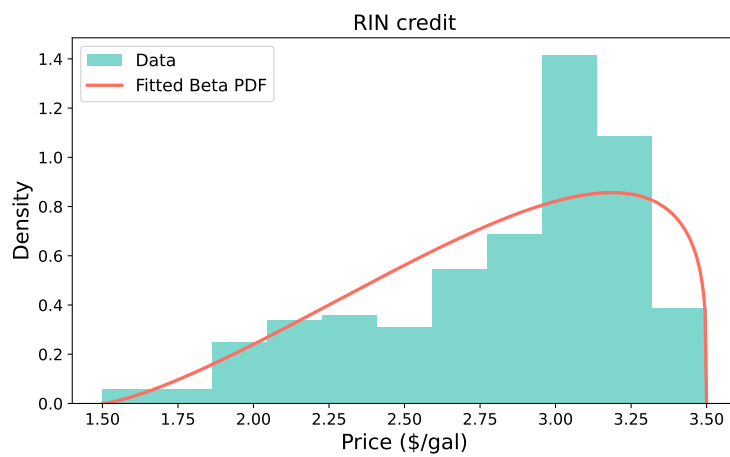


Fig. S9 Price distributions of D3 RIN credit [112].

S5 Additional Results

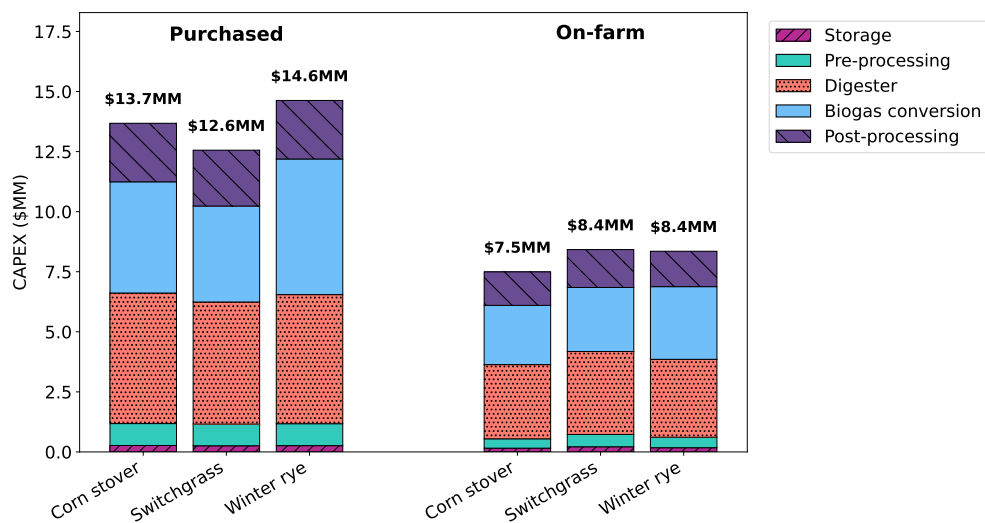


Fig. S10 Total capital investment (CAPEX) by unit operation for co-digestion scenarios producing electricity.

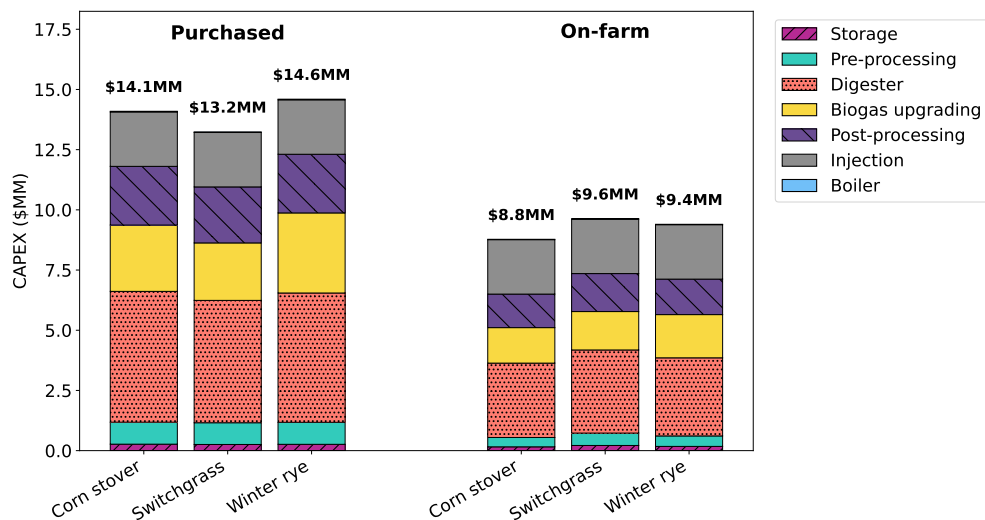


Fig. S11 Total capital investment (CAPEX) by unit operation for co-digestion scenarios producing renewable natural gas.

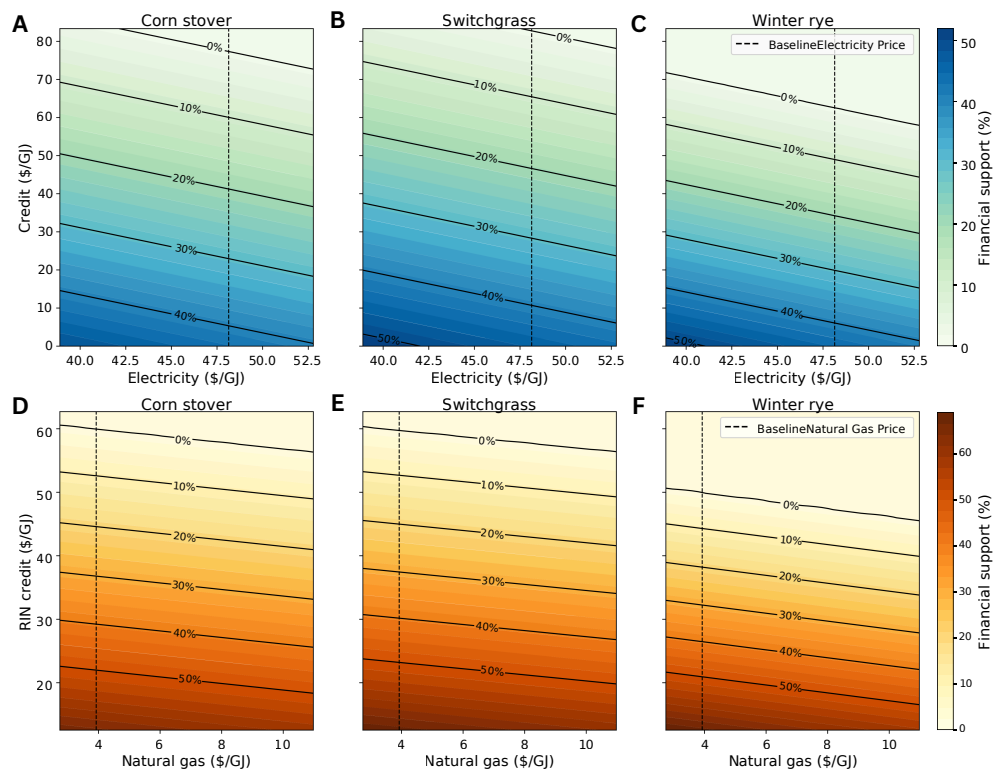


Fig. S12 Financial support necessary to achieve net present value equal to zero, expressed as a percentage of total capital investment, for (A, B, and C) electricity production and (D, E, and F) RNG production. Results from on-farm biomass scenarios only.

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