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National Greenhouse Gas Emission Reduction Potential from Adopting Anaerobic Digestion on Large-Scale Dairy Farms in the United States

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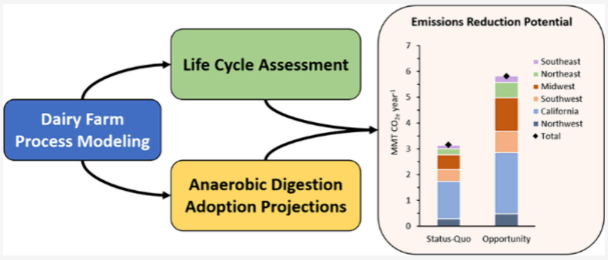
ABSTRACT: Waste-to-energy systems can provide a functional demonstration of the economic and environmental benefits of circularity, innovation, and reimagining existing systems. This study offers a robust quantification of the greenhouse gas (GHG) emission reduction potential of the adoption of anaerobic digestion (AD) technology on applicable large-scale dairy farms in the contiguous United States. GHG reduction estimates were developed through a robust life cycle modeling framework paired with sensitivity and uncertainty analyses. Twenty dairy configurations were modeled to capture important differences in housing and manure management practices, applicable AD technologies, regional climates, storage cleanout schedules, and methods of land application. Monte Carlo results for the 90% confidence interval illustrate the potential for AD adoption to reduce GHG emissions from the large-scale dairy industry by 2.45−3.52 MMT of CO_2-eq per year considering biogas use only in renewable natural gas programs and as much as 4.53−6.46 MMT of CO_2-eq per year with combined heat and power as an additional biogas use case. At the farm level, AD technology may reduce GHG emissions from manure management systems by 58.1−79.8% depending on the region. Discussion focuses on regional differences in GHG emissions from manure management strategies and the challenges and opportunities surrounding AD adoption.



KEYWORDS: *life cycle assessment, sustainability, decarbonization, renewable natural gas, combined heat and power, anaerobic digestion, dairy manure*

1. INTRODUCTION

Reducing global greenhouse gas (GHG) emissions is crucial to mitigate the effects of climate change. TheIntergovernmental Panel on Climate Change (IPCC) has identified the need to reduce GHG emissions by about 45% from 2010 levels by 2030 and reach net-zero emissions by 2050 to limit warming to 1.5 °C, with the current global trajectory falling far short of these critical targets.[1] In 2021, methane (CH_4) emissions from dairy manure management totaled 35.9 MMT CO_2-eq accounting for 54.4% of CH_4 emissions from livestock manure management, 4.9% of total CH_4 emissions, and 0.57% of gross annual GHG emissions in the United States.[2] Nitrous oxide (N_2O) emissions from dairy manure management totaled 5.5 MMT CO_2-eq in 2021 accounting for 31.6% of N_2O emissions from livestock manure management, 1.4% of total N_2O emissions, and 0.08% of gross GHG emissions in the United States.[2] Previous studies have shown that anaerobic digestion (AD) of dairy manure can effectively reduce emissions and provide environmental and economic benefits while displacing fossil fuels.[3−10] While enteric fermentation was the largest source of CH_4 emissions in the U.S. in 2021 totaling 195 MMT CO_2-eq (26.4% of total CH_4 emissions and 3.1% of gross GHG emissions), these emissions cannot be mitigated through AD technologies.[2]

Previous studies of AD have focused on specific aspects of the technology,[10−13] provided location-specific results,[7,9,14−16] or offered broad reviews of AD technologies and industry practices.[6,17] National assessments by agencies like the EPA[4] and USDA[18] have offered insights into regional manure management practices and potential CH_4 emission reductions from AD adoption. However, these studies primarily addressed CH_4 emission reduction and have often overlooked critical factors like N_2O emissions from certain livestock housing types, solid manure storage, and land application of residual solids and digestate. Moreover, these analyses heavily relied on

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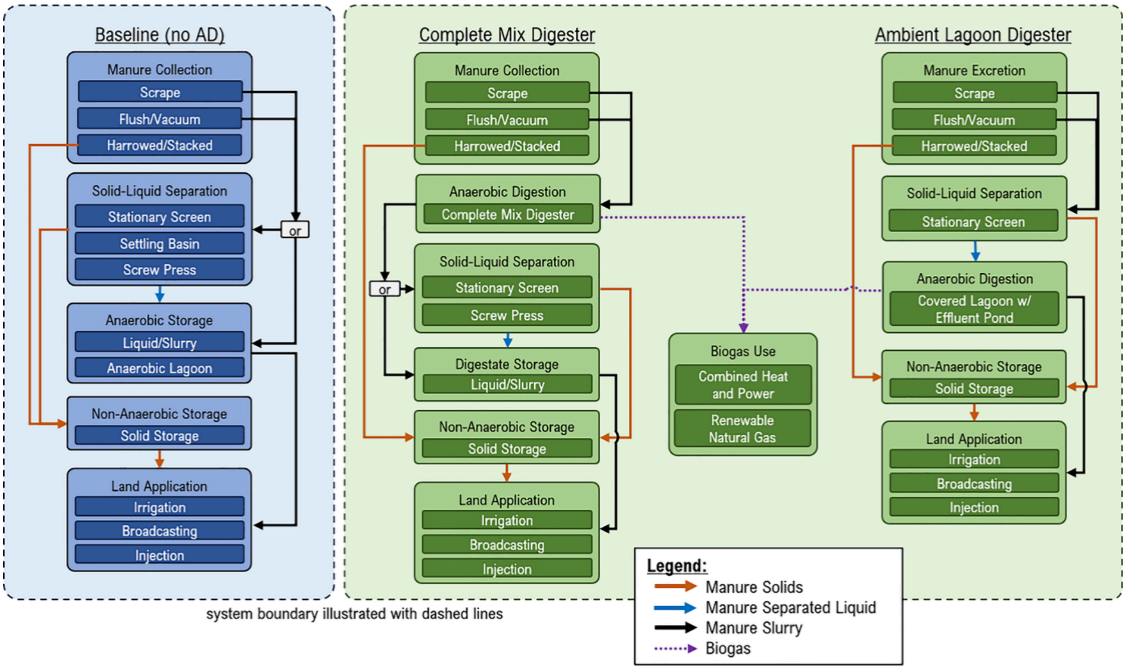

Figure 1. Process flow diagram illustrating the system boundary of the study and the various pathways captured by the 10 baseline scenarios and 10 anaerobic digestion (AD) scenarios.

census data, which limited their scope to historical and current observations, without considering future scenarios. Understanding the dairy industry's trajectory concerning regionally appropriate AD adoption is vital for determining national GHG emission trends and adjusting strategies for GHG mitigation and fossil fuel phase-out.

The objective of this study was to determine the potential reduction in CH_4 and N_2O emissions from adopting AD technologies on applicable large-scale dairy farms in the contiguous United States considering regional differences in climate and manure management strategies. Applicable dairy farms were identified as the large-scale operations that are most likely to adopt AD technology in the near term based on scale, logistics, and economic estimates. The study examines emission reduction under current incentives for renewable natural gas (RNG) production and explores the impact of incentivizing combined heat and power (CHP) as an additional biogas use case. Additionally, this study offers a robust modeling framework that can be used to evaluate farm-level emission reduction opportunities and explore alternative AD adoption scenarios.

2. MATERIALS AND METHODS

This study employs a systematic mass balance approach combined with life cycle assessment (LCA) methodology to quantify emissions of CH_4, N_2O, and anthropogenic CO_2 (resulting from nonbiological processes like diesel fuel combustion) across manure management systems (MMS), AD systems, and land application of residual manure and digestate. Regional manure management practices are represented through a detailed collection of baseline and adoption scenarios which are integrated with future technology adoption projections to quantify the national GHG emission reduction potential. Furthermore, modeling methodologies and region-specific modeling assumptions have been thoroughly reviewed and informed by the manure technology team (MTT), a panel of experts assembled by the Innovation Center for U.S. Dairy[19] with representatives from key dairy regions. Members of the MTT and their affiliations are provided in Table S35 in the Supporting Information.

2.1. Goal and Scope. The objective of this study is to conduct a detailed evaluation of a distinct segment within the U.S. dairy industry, specifically focusing on large-scale dairy farms. These farms are notable for their considerable GHG emissions and their dominant contributions to national milk production. The analysis zeroes in on large-scale dairies that have yet to implement AD technologies and are prime candidates for AD adoption. Accordingly, the research delineates baseline scenarios to document the existing GHG emission profile of these operations, while also quantifying the potential for emission reduction through the adoption of AD technology by this segment of the dairy industry. The analysis begins at the point of dairy cow feces and urine excretion and includes all downstream CH_4 and N_2O emissions. Baseline scenarios encompass emissions from animal housing, MMS, long-term storages, and land application of residual volatile solids (VS) and nitrogen (N). Adoption scenarios also include emissions from AD, biogas upgrading, and biogas end-use. The model comprises 10 baseline and 10 adoption scenarios spanning six U.S. dairy regions (Northwest, California, Southwest, Midwest, Northeast, and Southeast). Dairy regions were delineated by clustering states that share similar manure management practices and climates. California was evaluated as its own dairy region due to its large dairy industry, particularly in the San Joaquin Valley. Details on the contribution of manure from states within each of the five remaining regions can be found in the Supporting Information. Figure 1 presents a general process flow diagram outlining the modeled pathways for baseline and AD scenarios. Detailed diagrams for each modeled scenario and definitions of each manure management subsystem are available in the Supporting Information.

Table 1. Descriptions of Baseline (1A–3C) and Anaerobic Digestion (4A–6D) Scenarios Modeled

	% of manure collected								
scenario	stacked	flushed	vacuumed	scraped	solid–liquid separation[a]	anaerobic digestion[b]	biogas use[c]	long-term storage[d]	regions[e]
1A	90%	10%			SS	none	NA	UCL	NW, SW
1B	90%	10%			SB	none	NA	UCL	NW, SW
1C	60%		40%		SS	none	NA	UCL	NW, SW
1D	60%		40%		SB	none	NA	UCL	SW
2A				100%	SS	none	NA	LS	NW, SW
2B				100%	SP	none	NA	LS	MW, NE
2C				100%	none	none	NA	LS	NW, MW, NE
3A		100%			SS	none	NA	UCL	SE
3B	23%	77%			SS	none	NA	UCL	CA
3C	23%	77%			SB	none	NA	UCL	CA
4A	60%		40%		SS	CMAD	CHP	LS	NW, SW
4B	60%		40%		SS	CMAD	RNG	LS	NW, SW
5A				100%	SS	CMAD	CHP	LS	NW, SW
5B				100%	SP	CMAD	CHP	LS	MW, NE
5C				100%	SS	CMAD	RNG	LS	NW, SW
5D				100%	SP	CMAD	RNG	LS	MW, NE
6A		100%			SS	CL-EP	CHP	CL-EP	SE
6B		100%			SS	CL-EP	RNG	CL-EP	SE
6C	23%	77%			SS	CL-EP	CHP	CL-EP	CA
6D	23%	77%			SS	CL-EP	RNG	CL-EP	CA

[a]SS: stationary screen; SB: settling basin; SP: screw press. [b]CMAD: complete mix anaerobic digester; CLEP: covered lagoon with effluent pond. [c]NA: not applicable; CHP: combined heat and power; RNG: renewable natural gas. [d]UCL: uncovered anaerobic lagoon, LS: liquid/slurry; CL-EP: covered anaerobic lagoon with effluent pond. [e]NW: Northwest; SW: Southwest; MW: Midwest; NE: Northeast; SE: Southeast; CA: California.

Baseline scenarios are defined by the chosen methods for manure collection, solid–liquid separation, and long-term storage, while AD adoption scenarios are further differentiated by the chosen AD technology and biogas application. Five manure collection configurations were considered and are described here. For open lots, 90% of manure is stacked in dry solid storage and 10% is flushed from the milking parlor to treatment. For open lots with concrete feed alleys, 60% of manure is stacked in solid storage and 40% is vacuumed to treatment. For confined scrape and confined flush scenarios, 100% of manure is scraped or flushed to treatment. For the confined flush scenario specific to CA, 23% of manure is collected from exercise pens and stacked in solid storage and 77% of manure is flushed from barns/milking parlors to subsequent systems. Table 1 summarizes the key characteristics of each baseline and AD adoption scenario.

For baseline scenarios 1A–3C, long-term storage of liquid manure occurs in uncovered anaerobic lagoons (UCL) or liquid/slurry (LS) systems. For AD adoption scenarios 4A–5D, solid–liquid separation occurs after AD and long-term storage of digestate occurs in LS systems. For AD adoption scenarios 6A–6D, solid–liquid separation occurs prior to the covered lagoon with effluent pond (CLEP), which serves as the method of both AD and long-term storage. All modeled scenarios assume land application as the end-fate for stored manure (solid and liquid) and digestate.

2.2. Functional Unit. LCA results for regional manure management scenarios are presented using the functional unit of a wet cow equivalent (WCE). The functional unit inherently incorporates regional and temporal variations in milk and VS production, thereby enabling the results to serve effectively in both detailed regional and national assessments of dairy-related GHG emissions. This functional unit was chosen to represent realistic dairy operations which contain a dynamic mix of lactating (wet) and nonlactating (dry) dairy cows. This study assumes that an average dairy cow is lactating 305 days out of the year or roughly 85% of the time based on inventory data from the USDA National Agriculture Statistics Service (NASS).[20] Daily VS excretion is dependent on dairy cow mass, milk production, and caloric intake.[2] Thus, there is a significant difference in the daily VS excretion rates between wet and dry dairy cows.[2,21] The VS excretion rate of one WCE in a specific state can be calculated by eq 1:

$$\mathrm{VS}_{\mathrm{WCE},i} = 0.85\left(\frac{\mathrm{TAM}_{\mathrm{L}}}{1000}\right)\mathrm{VS}_{\mathrm{L},i} + 0.15\left(\frac{\mathrm{TAM}_{\mathrm{NL}}}{1000}\right)\mathrm{VS}_{\mathrm{NL},i} \tag{1}$$

where $\mathrm{TAM}_{\mathrm{L}}$ is the typical average mass of a lactating dairy cow, $\mathrm{TAM}_{\mathrm{NL}}$ is the typical average mass of a nonlactating or "dry" dairy cow, $\mathrm{VS}_{\mathrm{L},i}$ is the VS excretion per 1000 kg animal mass for lactating dairy cows in state i, and $\mathrm{VS}_{\mathrm{NL},i}$ is the VS excretion per 1000 kg animal mass for nonlactating dairy cows in state i. Regional VS and N excretion rates were derived using a weighted average of state-level data,[2,21] weighted by each state's share of cows in a region. These rates, along with state-level VS and N excretion data, are detailed in Tables S12 and S13 of the Supporting Information. Results for manure management scenarios and emission reductions are based on Holstein cows, which made up 79.9% of the U.S. dairy herd in 2020.[22] The analysis also considers the impact of increasing Jersey and mixed breed populations by incorporating TAM variability in the Monte Carlo uncertainty analysis. Replacement stock were excluded from the analysis due to a lack of uniform management practices throughout the defined dairy regions.

2.3. Life Cycle Assessment Methodology. LCA methodology following ISO 14040 and 14044 standards[23] was used to determine the global warming potential (GWP) of each baseline and adoption scenario, with the delta between scenarios representing the potential GHG reduction. GHG emissions are reported with the units of "CO_2 equivalents" (CO_2-eq) which include emissions of CO_2 (anthropogenic only), CH_4 (nonfossil), CH_4 (fossil), and N_2O multiplied by their respective impact factors of 1, 27, 29.8, and 273 kg CO_2-eq/kg gas and summed.[24] Total GHG emissions were normalized by the number of cows and time over which emissions occurred to determine the GWP in kg CO_2-eq per WCE per year (kg CO_2-eq WCE^{-1} yr^{-1}).

The system boundary of this study comprehensively includes both direct and indirect GHG emissions related to manure management and biogas generation, upgrading, and end-use. Notably, it does not account for biogenic CO_2—neither recognizing CO_2 capture through photosynthesis in feed production and grazing nor considering CO_2 emissions from the combustion of RNG. The analysis specifically covers biogenic CH_4 emissions from manure management, fugitive CH_4 leaks, N_2O emissions across all stages, and anthropogenic CO_2 emissions from diesel machinery. Additionally, anthropogenic CO_2 emissions resulting from the consumption of grid energy (both electricity and natural gas) and consumables for biogas upgrading are incorporated as indirect emissions within this study's framework.

Life cycle inventory (LCI) data were collected from various sources. State-level emission data for grid energy consumption and grid energy displacement credits CHP using captured biogas were sourced from the EPA's Emissions and Generation Resource Integrated Database (eGRID).[25] Average emissions for each of the 6 dairy regions were determined from these state-level data, as detailed in the Supporting Information. Owing to uncertainties in AD adoption timelines and the predominance of biological CH_4 and N_2O emissions over GHG emissions from grid energy consumption, a dynamic LCA framework addressing changing grid emissions was considered beyond the scope of the study. CH_4 and N_2O emissions related to CHP were sourced from Zamalloa et al.,[26] while CH_4 and N_2O tailpipe emissions from CNG vehicles were obtained from the EPA.[27] Emissions associated with diesel combustion for manure collection, tanker injection, and manure broadcasting were directly obtained from Aguirre-Villegas and Larson.[5] LCI data for consumables in biogas upgrading, heat generation with a natural gas boiler, and RNG pipeline transport were sourced from the EcoInvent Life Cycle Inventory Database (version 3.9.1)[28] through cutoff analysis and accessed via openLCA 1.11.0,[29] with additional details provided in the Supporting Information.

2.4. Regional Data. Region-specific inputs required for the modeling work included ambient temperature, VS and N excretion rates, and emissions associated with the electricity grid (described in Section 2.3). Monthly average temperatures (5-year averages from 2018 to 2022) for each state in the contiguous U.S. were obtained from the National Oceanic and Atmospheric Administration (NOAA)[30] and used to determine average monthly temperatures for each region. Average temperatures were used throughout the analysis to calculate the temperature-dependent Arrhenius factor, the temperature-dependent methane conversion factor (MCF) for solid storages, as well as the sensible heat input for heating anaerobic digesters. For California, the average temperature used in the analysis only included counties in the San Joaquin Valley as over 90% of the California dairy industry is located there. All state-level and regional average data are presented in the Supporting Information.

2.5. Methane Emissions from Baseline Scenarios. Baseline scenarios to characterize GHG profiles of current large-scale dairy operations were established across six regions, following two pathways: (1) manure flushed or vacuumed into uncovered anaerobic lagoons for storage and land application; or (2) manure scraped or vacuumed into liquid/slurry storage for eventual land application. Variations include the ratio of dry to wet storage, use of settling basins or solid−liquid separation, and land application methods. Table 1 details each of the modeled baseline configurations (1A−3C).

2.5.1. Methane Emissions from Nonanaerobic Storage. All modeled scenarios aside from 2C include nonanaerobic solid storage of VS removed through solid−liquid separation. Furthermore, nonanaerobic solid storage is the method of long-term storage assumed for the portion of manure collected from open lots in scenarios 1A−1D, 3B−3C, 4A−4B, and 6C−6D. Details on where these scenarios ocurr can be found in Table 1, while the number of cows considered under each scenario is available in Tables S29 and S31 in the Supporting Information. For estimating monthly methane emissions from solid storage, calculations followed the IPCC protocol[31] using temperature-dependent monthly MCF values for solid storage obtained from the "Reference" tab in the California Air Resource Board (CARB) version of the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model.[21] The portion of VS removed through solid−liquid separation was dependent on the selected separation technology, with separation efficiencies obtained from the "Reference" tab in the CARB GREET model[21] and the separation efficiency of sloped screen separators updated to 30% based on the work of Williams et al.[32] Detailed equations, solid−liquid separation efficiencies, and temperature-dependent MCF values for solid storage are provided in the Supporting Information.

2.5.2. Liquid/Slurry Storages. In the Northwest, Southwest, Midwest, and Northeast, baseline configurations with scrape manure collection delivered manure to liquid/slurry storages. These storages hold manure as excreted or with minimal water addition, for durations up to 4 years. Mechanical agitation ensured that specified monthly cleanout percentages corresponded to equivalent VS removal.[31] MTT recommendations informed regionally specific cleanout schedules, with some regions requiring 4 years for complete emptying. A monthly time step was used for VS input, regional cleanout schedules, and temperature-dependent Arrhenius factors. The Arrhenius factor was used to determine the portion of VS that was biologically available to degrade, and methane formation was determined by multiplying degraded VS by the maximum specific methane formation (B_0).[21] This monthly time step aligns with IPCC recommendations[31] and is essential for emission accounting in regions with significant temperature variations and variable VS loading. All baseline scenarios aside from 2C incorporated solid−liquid separation before long-term liquid/slurry storage, with emissions from separated solids covered in Section 2.5.1 and reduced VS loading accounted for in the VS mass balance.

When solids are not removed through solid−liquid separation prior to liquid/slurry storages, natural crust covers can develop and may reduce methane emissions by up to 40%.[31] IPCC recommendations state that this 40% reduction may be applied when a thick and dry crust cover is present.[31] This 40% reduction was not applied to scenario 2C in this study based on a unanimous decision from the MTT informed by first-hand observation suggesting that the majority of crust covers in liquid/slurry systems are cracked and bubbling rather than thick and dry. However, the MTT supported that bottom load slurry tanks often used by small dairies in the Northeast could apply this reduction.

2.5.3. Methane Emissions from Uncovered Ambient Lagoons. Ambient lagoons have lower depth, larger surface area, and lower total solids compared to liquid/slurry storages.[31] In baseline scenarios across the Northwest, California, Southwest, and Southeast, manure was delivered to ambient anaerobic lagoons for long-term storage. Unlike liquid/slurry systems, lagoons involve sequential VS flow from covered lagoons to uncovered effluent ponds, requiring a unique modeling approach. In the mass balance, degradable and nondegradable VS were separated to determine residual VS carried over each month, potentially degrading to produce CH_4. The degradable VS fraction entering the system was 51.7%, based on the maximum specific methane formation (B_0) for manure separated liquid[33] and reported biogas formation values per kg VS destroyed.[34]

Ambient lagoon systems provide flush water and irrigation water enriched by manure nitrogen.[31] VS used for flush water was assumed to return to the lagoon with minimal loss but using lagoon liquid for irrigation resulted in VS outflow from the system. Irrigation schedules reflecting regional practices were incorporated in the model and are presented in the Supporting Information. The model estimated VS leaving the lagoon in irrigation water by tracking monthly lagoon volume and using measured VS concentrations in lagoon flush water[34−36] to account for VS settling and the dynamic degradable vs nondegradable VS fraction. Published VS concentrations for CA were used in calculations for CA, the SW, and SE, while values for VS concentrations in Idaho were used for the NW. The possibility of additional regional variation was addressed by including these parameters in the Monte Carlo analysis of uncertainty. Degradable VS was multiplied by the temperature-dependent Arrhenius factor to determine monthly VS degradation. Total degraded VS was multiplied by 0.505 m^3 CH_4 kg VS degraded^{-1} to calculate monthly methane formation from lagoons.[34] Detailed equations for the mass balance, constants used for the Arrhenius factor, and calculations for lagoon volume approximations are provided in the Supporting Information.

Several baseline scenarios incorporated settling basins before lagoon storage to enable gravity settling and reduce lagoon system VS loading. The assumed 50% VS removal efficiency in these scenarios was based on work from Chastain and Henry.[37] Methane emissions from the 50% of VS retained in the settling basin were calculated with the same approach used for ambient lagoons. Mechanical agitation was assumed before settling basin cleanout. For baseline scenarios with settling basins preceding lagoons, the measured VS exit concentration of the lagoon[34−36] was multiplied by 50% to account for the VS retained in the settling basin.

2.5.4. Land Application of Residual Manure Solids. Following cleanout of solid and liquid storages, all residual manure solids and any accompanying liquids were assumed to be land applied through irrigation, tanker injection, or broadcasted in fields. Land application procedures defined for each region are provided in the Supporting Information. In general, this study assumed that the potential to produce methane would be significantly reduced once manure solids were removed from the anaerobic storage environment. This study assumed that any residual land applied carbon would be broken down by soil microbes and released to the atmosphere as biogenic CO_2.[21] Biogenic CO_2 emissions resulting from land application of residual manure solids were not counted as burdens to the system. However, emissions of N_2O following land application were considered burdens with the accounting methodology described in Section 2.8.

2.6. Anaerobic Digestion Adoption Scenarios. The AD technology chosen for regional adoption scenarios depended on the corresponding baseline scenario. Baseline scenarios with anaerobic lagoon storage were transformed into AD scenarios by installing a lagoon cover to capture 95% of produced biogas,[21,31] which was then directed to one of two biogas utilization scenarios detailed in Section 2.7. For scenarios involving covered lagoons, the monthly volume entering the effluent pond was assumed to equal the volume entering the lagoon, with flush and irrigation water sourced from the effluent pond. Methane emissions from effluent ponds were estimated using the same method applied to liquid/slurry storages. The total VS in the effluent pond for any given month was calculated as the balance between incoming VS (equivalent to the difference between VS entering the lagoon and VS destroyed through biogas formation) and VS leaving through effluent pond cleanout. Agitation was assumed before effluent pond cleanout. Methane emissions from effluent ponds were determined by multiplying the total VS in the system for a given month by the monthly Arrhenius factor and then by the maximum specific methane formation for manure separated liquid.[33]

Regions employing scrape collection and liquid/slurry storage were assumed to adopt an engineered complete mix anaerobic digester (CMAD). CMAD systems were assumed to operate in the mesophilic range at a fixed temperature of 36 °C requiring a sensible heat source to maintain this temperature throughout the year.[38−40] For CHP scenarios, waste heat was utilized for digester heating, supplemented by a natural gas boiler. In scenarios producing RNG, a natural gas boiler was used as a heat source. Detailed calculations for temporally resolved sensible heat input are available in the Supporting Information. CMAD units were assumed to achieve 85% of the maximum specific methane formation (B_0) due to constant reactor temperature and consistent VS loading throughout the year.[39,41] A sensitivity analysis exploring reactor efficiencies ranging from 30 to 100% is presented in the Supporting Information. CMAD reactors were assumed to leak 2% of produced biogas to the atmosphere based on prior studies.[21,31] Digestate containing the remaining 15% of VS was directed to liquid/slurry storage, with methane emissions calculated using the method described in Section 2.5.2. In all CMAD scenarios, digestate was subject to solid−liquid separation before long-term storage in liquid/slurry systems, resulting in reduced VS loading to long-term storage. Methane emissions from solid storage of separated VS from AD digestate were determined following the methodology described in Section 2.5.1.

2.7. Biogas Use. Two pathways were modeled for biogas use: (1) direct use in CHP; (2) biogas upgrading, compression, and pipeline transport for use in CNG vehicles. Thermal and electrical efficiencies for CHP were informed by Zamalloa et al.[26] and the "Reference" tab in the CARB GREET model.[21] Heat generated through CHP was assumed to be used onsite to heat CMAD systems, with any excess heat considered a burden-free waste product. Electricity generated through CHP was assumed to be sold directly to the local grid, with the system earning a grid emission avoidance credit equal to the carbon intensity (kg CO_2-eq kWh^{-1}) of the regional grid.

In the second biogas-use scenario, raw biogas was upgraded to vehicle-ready CNG based on the process described by Skorek-Osikowska et al.[42] for biogas produced through AD of dairy manure. Indirect emissions for consumables used in the biogas upgrading process including iron(II) chloride, calcium hydroxide, monoethanolamine (MEA), tap water, wastewater treatment, and process electricity were considered. The model included 3% parasitic consumption of biogas for process heat and 2% loss to fugitive emissions based on Skorek-Osikowska et al.[42] Furthermore, the CNG pathway included emissions for pipeline transport of 1000 km.[28] Biogenic CO_2 captured in the upgrading process was assumed to be vented to the atmosphere with no burden to the system. Once delivered to a CNG station, the model assumed 90% use in CNG buses with an assumed average fuel economy of 4 miles per diesel gallon equivalent (DGE) and 10% use in CNG passenger vehicles with an assumed average fuel economy of 25 miles per DGE. Miles driven by each type of vehicle were used to determine tailpipe emissions of CH_4 and N_2O.[43] The total production of DGE from captured biogas was determined by multiplying the energy content of RNG[42] expressed in DGE by an adjustment factor of 0.9 to account for the difference in engine efficiency between diesel and CNG vehicles.[21] For every DGE of CNG delivered to the station, the system received a diesel displacement credit equal to the well-to-wheel emissions for petroleum-based diesel of 92 g CO_2-eq MJ $fuel^{-1}$ obtained from the GREET Life Cycle Inventory model.[44] Further details for both biogas-use pathways are included in the Supporting Information.

2.8. N_2O Emission Accounting. This study includes both direct and indirect emissions of N_2O resulting from the various manure management scenarios considering the impacts of solid−liquid separation, the method of manure storage or digestion, and the method of land application of residual manure solids. State-level nitrogen excretion data for dairy cows were obtained from the EPA[2] and used as the starting point of the nitrogen mass balance for each scenario. Next, nitrogen losses and resulting N_2O emissions from each subprocess were determined using the protocol outlined in the IPCC 2019 Refinement to the 2006 Guidelines for Greenhouse Gas Inventories.[31] The fraction of manure nitrogen volatilized, lost to leaching, and all applicable N_2O emission factors for the various manure management strategies in the regional scenarios are provided in the Supporting Information.

Results from previous studies[45−48] were used to estimate the nitrogen removed through solid−liquid separation with screw press and stationary screen separators. A total nitrogen removal of 15% of incoming nitrogen was assumed for scenarios involving solid−liquid separation. Furthermore, storage of separated solids was assumed to ocurr in an aerobic environment, resulting in negligible N_2O emissions from storage and land application. Emission factors were developed for each method of land application considering the impacts of manure digestion on N_2O formation, and the full assessment and resulting N_2O emission factors are provided in the Supporting Information.

2.9. Anthropogenic Emissions from Manure Management Energy. GHG emissions associated with diesel consumption for equipment used for manure scraping, vacuuming, and tanker trucks used for manure broadcasting and injection were obtained directly from Aguirre-Villegas and Larson.[5] Estimates for grid electricity consumption for flush water pumping, manure pumping, mechanical agitation of manure storage systems, irrigation, and solid−liquid separation were obtained from Aguirre-Villegas and Larson[5] and multiplied by the carbon intensity of regional electricity grids to determine total indirect GHG emissions for each scenario. Energy consumption values for mechanical mixing of CMAD systems were based on previous studies.[8,45,49]

2.10. Regional Adoption Projections. Two AD adoption cases were developed in this study. The status quo adoption case reflects the current landscape of AD adoption on large-scale dairy farms. In this scenario, adoption is primarily driven by the economics of producing RNG for the California Low Carbon Fuel Standard (LCFS) market, the U.S. EPA Renewable Fuel Standard (RFS) D3 RINs, and renewable CNG sales. The opportunity case expands on this and considers future incentive programs like the EPA RFS eRIN Program via CHP for electricity production, which requires less capital and operational complexity, providing opportunities for smaller dairy farms.

Forecasting AD adoption for dairy farms is complicated by existing practices, farm dynamics, RNG pipeline access, and changing policy. A full techno-economic analysis was considered outside the scope of the study. Instead, a high-level economic analysis was developed, leveraging input from digester developers and industry experts to assess the economic viability of AD adoption. Capital cost, operating cost, farm configuration, and revenue were used to estimate the required number of mature cows to ensure economic viability for large-scale digester facilities. The status quo case considered the number of cows in the 2500−4999 and 5000+ NASS categories with an estimated threshold of 3500 mature cows required for AD adoption. The opportunity case augmented the status quo case with the addition of cows in the 1000−2499 NASS category and an estimated threshold of 1750 mature cows. Where the average number of cows per farm fell short of the threshold for a given region, a simplifying assumption was made that smaller farms could form clusters to achieve the total number of cows predicted for each region. In these scenarios, a central digester processes manure from several farms, or a central biogas upgrading facility collects and processes biogas from multiple farms.

First-order economic estimates considered the top 10 milk-producing states plus Florida and Arizona, resulting in 76% of the U.S. dairy herd and giving the estimates a built-in safety factor. Florida was chosen as the representative state for the Southeast and has the largest number of mature cows in the 1000+ NASS category in the region. Arizona was selected based on significant state-wide efforts to adopt AD technology with 84,514 cows currently contributing to digesters. Furthermore, it ranks 14th in total milk production and has the second largest average herd size in the United States. Further details on the economic estimates can be found in the Supporting Document titled "Economic_Analysis_Status-Quo_and_Opportunity_V5.xlsx". Table 2 provides a summary at the regional level of the participating cows considered for each adoption scenario. A detailed explanation of the adoption estimation approach is provided in the Supporting Information.

2.11. Sensitivity Analysis. Model sensitivity was analyzed using single-factor sensitivity analysis across 128 parameters,

Table 2. Summary of AD Adoption Estimates by State and Region

region	state	participating cows (status quo)	participating cows (opportunity)
Northwest	Washington	70,000	109,900
	Idaho	45,500	112,000
California	California	309,091	515,909
Southwest	Arizona	35,280	75,800
	New Mexico	0	65,757
	Texas	114,720	207,362
Midwest	Michigan	70,000	111,580
	Minnesota	17,500	50,260
	Wisconsin	38,500	129,063
Southeast	Florida	31,500	54,250
Northeast	New York	42,000	110,040
	Pennsylvania	10,500	21,840

each altered by ±20% from baseline to assess impacts on emission reductions, both regionally and nationally, for each adoption case. Parameters affecting emission reductions by >10% (21 in total) were then used in a Monte Carlo uncertainty analysis, with detailed results in the Supporting Information.

2.12. Monte Carlo Analysis of Uncertainty. Model uncertainty was evaluated via Monte Carlo analysis in JMP Statistical Software,[50] focusing on 21 key parameters identified through sensitivity analysis. Parameter distributions, informed by published data and expert input, are detailed in the Supporting Information. The analysis examined regional and national emission reduction under the status quo and opportunity scenarios, running 5000 iterations per scenario and randomly selecting parameter values within the defined distributions. Results, including a 90% confidence interval for emission reductions, are analyzed at the regional and national level for both adoption scenarios.

3. RESULTS AND DISCUSSION

Net GHG emissions per WCE per year for 10 baseline scenarios (1A through 3A) and 10 AD adoption scenarios (4A through 6B) are shown in Figure 2. Regional differences in climate and storage practices lead to varying net GHG emissions in both baseline and adoption scenarios. Reduction in direct farm-level emissions from manure management through AD adoption ranged from 58.2% in the Southwest to 78.8% in the Northeast.

The highest emissions among baseline scenarios occur in California (scenario 3C), with significant methane emissions from settling basins and uncovered lagoons, totaling 7.54 MT CO_2-eq WCE^{-1} yr^{-1}. Following is scenario 2C, with 6.39, 6.31, and 5.74 MT CO_2-eq WCE^{-1} yr^{-1} in the Northeast, Midwest, and Northwest, respectively. Scenario 2C employs liquid/slurry storage without upfront VS removal through solid–liquid separation, resulting in higher emissions compared to scenarios 2A and 2B, which remove 30% of VS before storage. The VS removed through solid–liquid separation is stored in nonanaerobic solid storage prior to land application with negligible emissions from manure broadcasting (please see Table S26 for more details). Use of solid–liquid separation reduces emissions by 29.4% in the Northwest (2C vs 2A) and 25% in the Midwest and Northeast (2C vs 2B). The percentage of VS removed prestorage correlates closely with emission reduction, emphasizing the potential benefits of technologies like centrifugation with higher VS removal rates.

Baseline scenarios using ambient lagoons for long-term storage without settling basins (3A and 3B) exhibit emissions similar to 2A, 2B, and 2C, ranging from 5.66 MT CO_2-eq WCE^{-1} yr^{-1} in California to 6.31 MT CO_2-eq WCE^{-1} yr^{-1} in the Southeast. Open lot scenarios 1A and 1B, storing 90% of manure in nonanaerobic solid storage, display the lowest emissions, indicating that anaerobic storage conditions significantly affect methane formation. Emissions from 1A range from 2.60 to 2.64 MT CO_2-eq WCE^{-1} yr^{-1}, while 1B varies from 2.63 to 2.80 MT CO_2-eq WCE^{-1} yr^{-1}. Increased

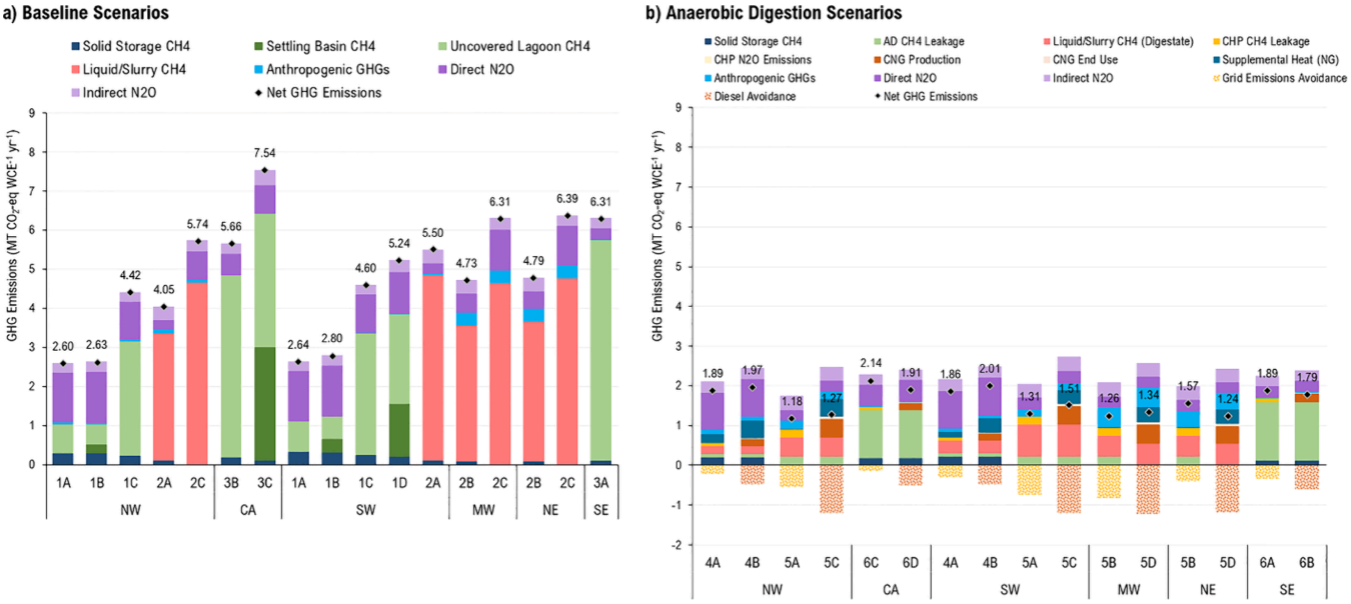

Figure 2. GHG emissions per wet cow equivalent per year for each of the regional baseline (a) and anaerobic digestion (b) scenarios in the system engineering model (AD: anaerobic digestion; CHP: combined heat and power; CNG: compressed natural gas; NG: natural gas; GHG: greenhouse gas). Scenario descriptions are presented in Table 1.

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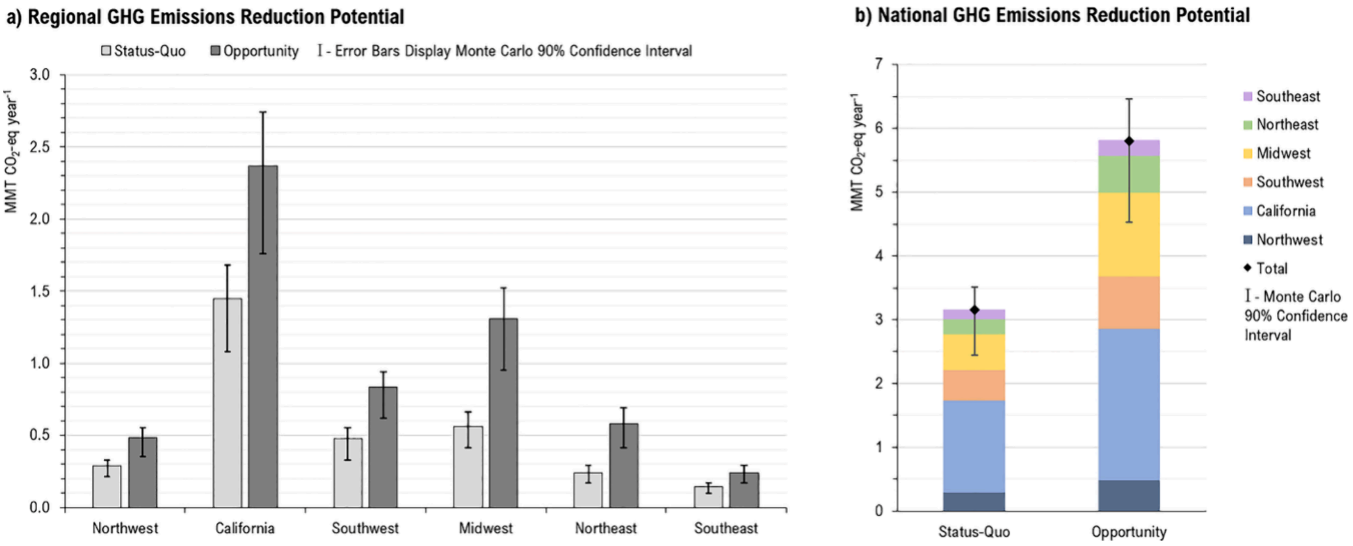

Figure 3. Regional GHG emission reduction potential from adopting AD technology for the status quo and opportunity adoption cases (a) and contribution of each region to the total national GHG reduction potential under both adoption cases (b). Error bars display the 90% confidence interval for 5000 simulation outputs from the Monte Carlo analysis of uncertainty.

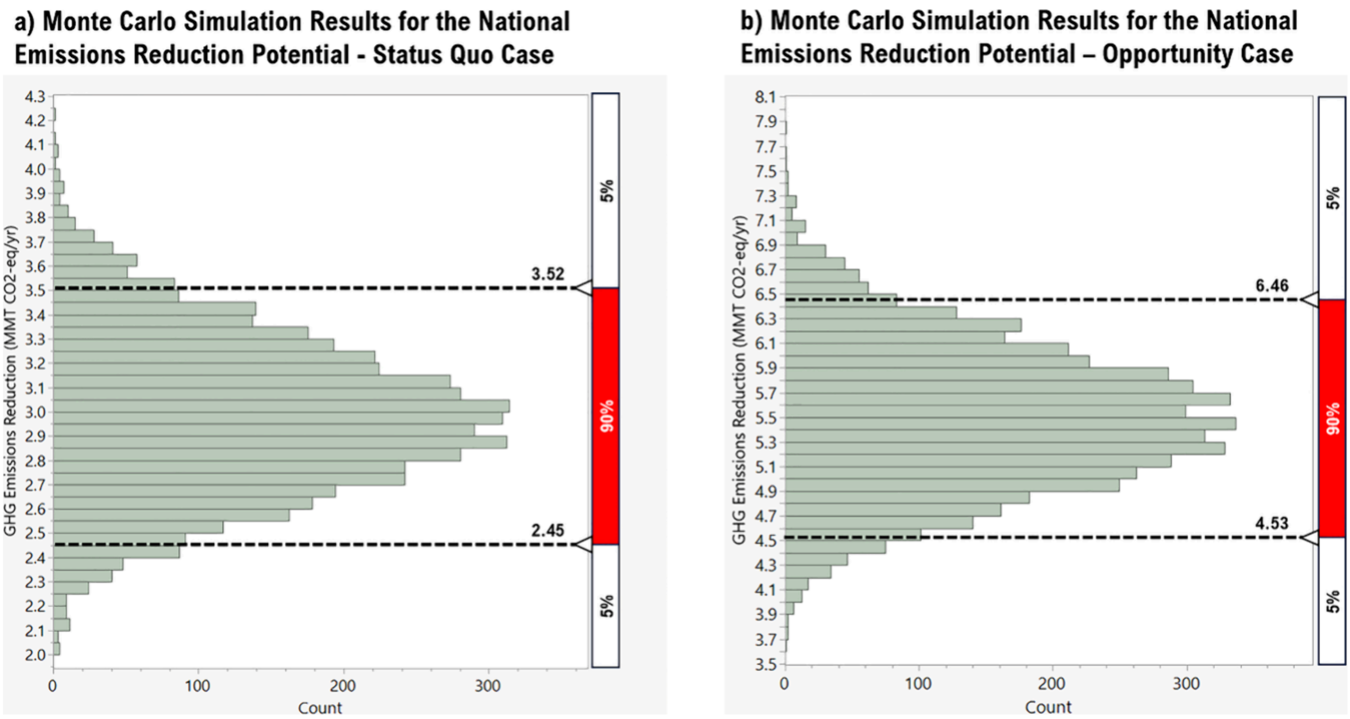

Figure 4. Monte Carlo simulation output summary showing the national emission reduction potential under the status quo (a) and opportunity (b) adoption cases. Each figure displays the 90% confidence interval from 5000 simulations.

nonanaerobic storage reduces methane but raises N_2O emissions, contributing 56−59% of net GHG emissions in 1A and 1B in the Northwest and Southwest, compared to 14.5% in the highest methane emitting scenario, 3C.

For the various AD adoption scenarios (Figure 2b), the highest emissions result from scenario 6C, which utilizes a covered lagoon digester. Net emissions for these lagoon digester scenarios range from 1.79 MT CO_2-eq WCE^{-1} yr^{-1} in the Southeast to 2.14 MT CO_2-eq WCE^{-1} yr^{-1} in California. The increased emissions for covered lagoon systems relative to other adoption scenarios can be attributed to higher methane leakage rates from lagoons (5% as opposed to 2% in CMAD systems). Scenarios 4A and 4B show the next highest emissions ranging from 1.86 to 2.01 MT CO_2-eq WCE^{-1} yr^{-1}. These scenarios are representative of open lot scenarios with manure on concrete, resulting in 40% of manure sent through the CMAD and 60% of manure managed in nonanaerobic storage. These collection percentages result in unfavorable conditions in which the potential diesel and grid emission avoidance credits are not maximized, and N_2O emissions dominate the emission profile due to the majority of manure managed in nonanaerobic solid storage. In scenarios 4A−4B, the contribution of N_2O to the total GHG burdens ranges from 50 to 58%. The lowest emissions among the AD adoption scenarios are from confined scrape systems (scenarios 5A, 5B, 5C, and 5D) in which 100% of manure is collected and sent through the CMAD, maximizing diesel and grid emission avoidance credits while minimizing methane leaks and N_2O emissions from nonanaerobic solid storage. Net GHG emissions for scenarios 5A−5D range from 1.18 MT CO_2-eq WCE^{-1} yr^{-1} in the Northwest to 1.57 MT CO_2-eq WCE^{-1} yr^{-1} in the Northeast, with N_2O emissions contributing 24−36% of total GHG burdens.

The regional GHG emission reduction potential as well as the total national GHG emission reduction potential from adopting AD technologies on large-scale dairy farms in the U.S. is shown in Figure 3.

Regional reductions under status quo assumptions range from as little as 0.14 MMT CO_2-eq per year in the Southeast to as high as 1.45 MMT CO_2-eq per year in California. Status quo adoption correlates to a total national GHG reduction potential of 3.15 MMT CO_2-eq per year. Under the opportunity adoption case, these figures increase to 0.24 MMT CO_2-eq per year in the Southeast, 2.37 MMT CO_2-eq per year in California, and a national GHG emission reduction of 5.82 MMT CO_2-eq per year, highlighting the improved emission reduction opportunity for the dairy industry throughout the U.S. from incentivizing CHP on smaller farms. From a regional perspective, the greatest emission reduction opportunities from AD adoption are in California (1.45 to 2.37 MMT CO_2-eq per year), the Midwest (0.56 to 1.31 MMT CO_2-eq per year), and the Southwest (0.47 to 0.83 MMT CO_2-eq per year).

These values can be compared to other national GHG assessments. The status quo and opportunity adoption scenarios yield reductions of 7.6 and 14.1%, respectively, in total GHG emissions from all U.S. dairy manure.[2] The entire life cycle GHG emissions associated with U.S. milk production is approximately 97 MMT CO_2-eq per year.[51] Accounting for 15% of manure emissions allocated to beef cattle in the farmgate LCA,[51] these reductions translate to 3.8 and 7.1% reductions in total GHG emissions from all U.S. milk production for the status quo and opportunity adoption scenarios, respectively. The reductions quantified in this study represent a smaller portion of overall industry emissions. However, farm-level emission reductions between baseline and AD scenarios range from 58.1 to 78.8%, depending on the region. These farm-level reductions surpass the IPCC's 45% target by 2030,[1] underscoring the need for faster AD adoption across all industry levels to achieve greater emission reductions and mitigate climate change impacts.

Figure 4 displays the Monte Carlo analysis results, outlining the uncertainty bounds for estimated emission reductions due to variability in key model inputs. The 90% confidence interval indicates that national emissions could decrease by 2.45 to 3.52 MMT CO_2-eq annually under the status quo case, accounting for a 5.9−8.5% reduction in U.S. dairy manure management emissions. The opportunity case shows a potential reduction of 4.53 to 6.46 MMT CO_2-eq per year or 10.9−15.6%. The sensitivity analysis reveals that activation energy and bioassay temperature, key factors in calculating the Arrhenius factor, significantly influence these estimates. Detailed regional results and further sensitivity analysis data are provided in the Supporting Information.

For another point of comparison, carbon intensity (CI) scores are offered in the Supporting Information for electricity and RNG per MJ of energy when going from each baseline scenario to each adoption scenario in each respective region.

3.1. Other Potential Environmental Impacts. In discussing the environmental ramifications of land applying digestate from the AD of dairy manure, it is crucial to consider a spectrum of potential impacts beyond the primary goal of GHG emission reduction. While digestate application can enrich soil nutrients and reduce the need for synthetic fertilizers, it also presents challenges. For instance, the high nutrient content, particularly nitrogen and phosphorus, can lead to nutrient runoff into water bodies, potentially exacerbating eutrophication in aquatic ecosystems.[52] Moreover, the application of digestate must be carefully managed to prevent the leaching of nitrates into groundwater, posing risks to water quality and public health. Additionally, the presence of pathogens and pharmaceutical residues in digestate requires attention, as improper handling and application can affect soil health and biodiversity. As the AD process converts organic matter into more stable forms, there is also a potential impact on soil carbon sequestration capacities, which warrants further investigation to fully understand the balance between emission reductions and potential trade-offs in soil carbon dynamics. Therefore, while the land application of digestate offers a sustainable waste management solution, it necessitates a holistic assessment of environmental impacts to optimize benefits and mitigate adverse effects.

3.2. Recommendations. There are several limitations in this modeling approach. The monthly time step used for methane calculations and the annual time step for N_2O emissions could benefit from increased temporal resolution. Thermal modeling to estimate the actual temperature of ambient lagoons and liquid/slurry storages was not included, relying on ambient temperature data. Expanding the system boundary to include feed production and including biogenic carbon accounting in the framework could further enhance the accuracy of the results. Further validation of study results with farm-level data is imperative to confirm the reliability and accuracy of the identified emission reduction potential. Actual AD adoption will depend heavily on economic viability, which relies on dynamic factors such as carbon markets, government subsidies, milk production, and other economic influences. The preliminary economic modeling performed in this study does not consider these dynamic factors in adoption estimates and introduces uncertainty into the emission reduction estimates. Lastly, this study considered larger-scale dairy; however, the combination of technical innovation coupled with policy has the potential to reduce the size of dairy farms adopting AD. Despite these limitations, this study offers valuable insights from the expanded system boundary and inclusion of N_2O emissions. Additionally, extensive peer review and discussion from the MTT have ensured that regional modeling assumptions are aligned with actual industry practices.

Several strategic recommendations emerge from this study to enhance GHG reduction through AD adoption in the U.S. dairy industry. Scenario-specific results highlight the promise of AD adoption in confined scrape systems with 100% manure collection. These systems benefit from reduced N_2O emission and maximized diesel or grid emission avoidance credits. In lagoon systems, increasing the biogas collection efficiency of installed liners can yield further GHG reductions. Additionally, enhancing solid−liquid separation processes with technologies that achieve higher VS removal rates can provide further reductions in life cycle emissions. The introduction of targeted policy incentives, such as subsidies or tax incentives, is recommended to encourage adoption among smaller farms and support transitions to more efficient MMS. A comprehensive environmental assessment of digestate application is crucial to ensure that GHG reduction benefits are not offset by other environmental risks such as nutrient runoff and groundwater contamination. These recommendations aim to guide industry stakeholders in implementing strategies that align with national and global sustainability goals.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.4c00367.

> Detailed model structure and critical assumptions, equations used to calculate CH_4, N_2O, and anthropogenic CO_2 emissions for all scenarios, additional results, and discussion (PDF)
>
> Economic analysis used to develop AD adoption projections (XLSX)

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Author Contributions

The manuscript was written through the contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

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