Contribution of Anaerobic Digesters to Emissions Mitigation and Electricity Generation Under U.S. Climate Policy

David P. M. Zaks,[*,†] Niven Winchester,[‡,§] Christopher J. Kucharik,[†,∥] Carol C. Barford,[†] Sergey Paltsev,[‡] and John M. Reilly[‡]

[†]Center for Sustainability and the Global Environment, Nelson Institute for Environmental Studies, University of Wisconsin—Madison, 1710 University Avenue, Madison, Wisconsin 53726, United States

[‡]Joint Program on the Science and Policy of Global Change, Massachusetts Institute of Technology (MIT), 77 Massachusetts Avenue, MIT E19- 411, Cambridge, Massachusetts 02139-4307, United States

[§]Department of Economics, University of Otago, PO Box 56, Dunedin 9054, New Zealand;

[∥]Department of Agronomy, University of Wisconsin—Madison, 1575 Linden Drive, Madison, Wisconsin 53706, United States

S *Supporting Information*

ABSTRACT: Livestock husbandry in the U.S. significantly contributes to many environmental problems, including the release of methane, a potent greenhouse gas (GHG). Anaerobic digesters (ADs) break down organic wastes using bacteria that produce methane, which can be collected and combusted to generate electricity. ADs also reduce odors and pathogens that are common with manure storage and the digested manure can be used as a fertilizer. There are relatively few ADs in the U.S., mainly due to their high capital costs. We use the MIT Emissions Prediction and Policy Analysis (EPPA) model to test the effects of a representative U.S. climate stabilization policy on the adoption of ADs which sell electricity and generate methane mitigation credits. Under such policy, ADs become competitive at producing electricity in 2025, when they receive methane reduction credits and electricity from fossil fuels becomes more expensive. We find that ADs have the potential to generate 5.5% of U.S. electricity.

INTRODUCTION

As demand for food and energy grows, innovative ways to meet demand while enhancing environmental quality will be needed. Anaerobic digesters (ADs) can produce renewable energy from livestock manure, prevent the release of methane, and reduce air and water pollution, and digested manure can be applied to crops as a fertilizer.[1] Most ADs in the U.S. sell electricity and digested manure, but the net present value of most systems is insufficient to promote widespread adoption.[2,3] Placing an economic value on the climate, energy, and environmental benefits that ADs provide can help to accelerate their deployment.

Deployment of renewable energy technologies grows under climate policy compared to business-as-usual.[4] Although support for ADs in the U.S. has been limited,[5] countries such as China,[6] India,[7] and Germany [8] have higher rates of AD adoption, mostly due to government support and financial incentives. The incentives currently available at the local, state, and federal levels in the U.S. have stimulated some AD projects. Comprehensive inclusion of the GHG mitigation benefits and low-carbon energy generation of AD projects within a federal climate and energy policy would further enhance prospects for new projects.

Although economic and environmental models have tested the integration of many renewable energy technologies,[4,9,10] a rigorous evaluation of ADs within a computable general equilibrium model has yet to be completed. We used an economic model to test the effects of a representative climate stabilization policy on the penetration of ADs as a GHG mitigation and low-carbon energy generation technology in the U.S. agriculture sector. Engineering and life-cycle data were used to calculate the cost of electricity from a typical AD system.[11,12] Spatially explicit livestock density maps[13] and state-level methane emissions data[14] were used to estimate potential electricity generation capacity and emissions reductions from livestock manure. The climate policy scenarios simulated in the economic model included a reference case and an emissions reduction of 50% below 2005 levels by 2050.[4] As carbon dioxide equivalent (CO_2e) emissions prices increased under more stringent caps, AD systems became competitive, in part, because of additional credits for methane mitigation. Unlike most other low-carbon energy sources, ADs deliver additional nonmarket environmental benefits.

ANAEROBIC DIGESTERS

Over the last century, as farms have become more specialized, nutrient cycling between crops and livestock has been decoupled.[15] Crop nutrient needs are increasingly met with off-farm resources, while the storage and land application of manure from livestock operations continues to have negative environmental impacts.[16] Agriculture accounts for 6% of greenhouse gas emissions in the United States.[14] Manure stored in anaerobic pits or lagoons supports environmental conditions for methane-producing bacteria, and these emissions account for 0.8% of U.S. emissions (26% of agricultural methane emissions and 9% of CO_2e emissions from agriculture).[14] Diverting manure away from traditional management techniques to ADs can have multiple benefits.[17] First, biogas, which is a mixture of methane, carbon dioxide, and trace gases such as hydrogen sulfide, can be combusted on-site in a generator. The electricity produced may offset purchased power or be fed into the electricity grid. Alternatively, biogas can undergo an upgrading process that results in an almost pure stream of methane that can be injected into natural gas pipelines.[18] Energy generated by ADs can attract low-carbon energy subsidies if life-cycle emissions are taken into account.[19] Second, digested manure that remains after the AD process can be separated into solids that may be used as a soil amendment or replacement for livestock bedding, and liquid that can be used as fertilizer. The AD process mineralizes nutrients, leading to improved crop uptake and increased crop yields.[20]

Whereas the sale of energy has direct economic benefits, anaerobic digestion of manure also performs several functions that have little current market value. First, during the typical 21 days that manure travels through a mesophilic AD, microbial activity and a constant ~38 °C temperature break down the volatile compounds which are responsible for the malodorous qualities of other manure management systems, and kill weed seeds and pathogens such as *Salmonella* spp. and *E. coli*.[17,21] Second, when manure is separated postdigestion, most of the phosphorus remains in the solid portion, which can be recycled as livestock bedding or added to phosphorus-deficient soils.[22] The liquid portion of manure contains most of the nitrogen, which is converted in the digestion process to ammonium and is more readily available for plant uptake.[23] Separation of nutrients provides the opportunity to divert digestate from areas where soils are already nutrient enriched and additional nutrient loading could harm water quality. Processes to remove phosphorus in solid form are currently under development, but not ready for widespread deployment.[24,25] Finally, both market and nonmarket benefits of ADs, when compared to traditional manure management techniques, can increase and diversify farm income and maintain farmland.[26] Although factors in the decision to install an AD are primarily economic, valuing environmental benefits that are currently outside of the traditional market system may increase the financial viability of projects and accelerate their deployment.

The EPA estimates that the number of ADs in operation on U.S. farms has grown from 30 to 150 between 2002 and 2010 and can be attributed to demonstrated production and reliability, reduction of environmental impacts, state and federal funding programs, energy utility interest, and revenue potential.[27] Even with the 5-fold growth of ADs in the past decade, many roadblocks need to be removed in order to realize the climate, air, water, and development benefits that would accompany a widespread adoption. These barriers include high initial capital costs, uncertain accounting for current nonmarket benefits (including methane emissions), low farmer acceptance, difficult utility connections, and state and federal government regulations.[28,29]

METHODS

The MIT Emissions Prediction and Policy Analysis (EPPA) model was used to test a range of scenarios to quantify the economic and environmental responses to the introduction of ADs. EPPA is a recursive dynamic, multiregional, multisector computable general equilibrium model that simulates the world economy.[30] The model has been applied to a range of policy-relevant topics including energy legislation,[4,31] health,[32] biofuels,[9] agriculture,[33] and alternative energy technologies.[34] In this study, we compared the impacts of three scenarios on the use of electricity from ADs as a substitute for more carbon-intensive sources.

Anaerobic digesters are introduced into the model as a low-carbon alternative technology, in which the electricity produced competes with traditional electricity sources based on the levelized cost of electricity (LCOE) across sources with additional consideration of intermittency and experience with technology.[35] The LCOE takes into consideration the capital, operations, and fuel costs of electricity produced over the lifetime of the plant.[12] With no climate policy in place, alternative electricity generation technologies such as solar and wind power are one to four times more expensive than fossil-fuel-based generation.[12]

We compare three scenarios in EPPA to gauge the impact of ADs under climate legislation. The first, or reference scenario, assumed no climate policy. The policy scenarios described in refs 4 and 31 cover the range of recent Congressional proposals and are referred to by the cumulative number of GHG emission allowances each policy issues between 2012 and 2050. Our remaining scenarios implemented a representative U.S. climate policy, one with ADs available and one without. The policy specified an economy-wide emissions cap on all GHGs beginning in 2010. The 2010 cap was 95% of 2005 emissions in 2010 and was progressively lowered to 50% of 2005 emissions by 2050.

Version 5 of EPPA disaggregates the agricultural sector into separate crop, livestock, forestry, and biofuels production structures as described by ref 36. We modified the model to include livestock manure output and separate livestock production into traditional livestock, for which manure is treated as a byproduct, and livestock for which manure can potentially be used in ADs. Detailed changes to the model are described in the Supporting Information (SI) Methods and Figure S1. Livestock within the new production function is eligible for offsets from reduced emissions of methane, and income from the sale of electricity. The AD production structure employs capital, labor, and intermediate inputs from other industries to produce electricity (Figure S1).

ADs enter endogenously in EPPA when they become economically competitive with other forms of generation. Similar to other technologies within EPPA, ADs are parameterized using bottom-up engineering, life cycle and fuel cost data.[11] There are several types of ADs currently in use that range in size from 50 to 2800 kW ($n = 55$, mean = 573).[37] Acknowledging that there are several digester designs that operate best with certain feedstocks or in certain geographies, we based our analysis on capital cost data from horizontal plug flow ADs, as the most data were available from this technology.[37] The LCOE from ADs is
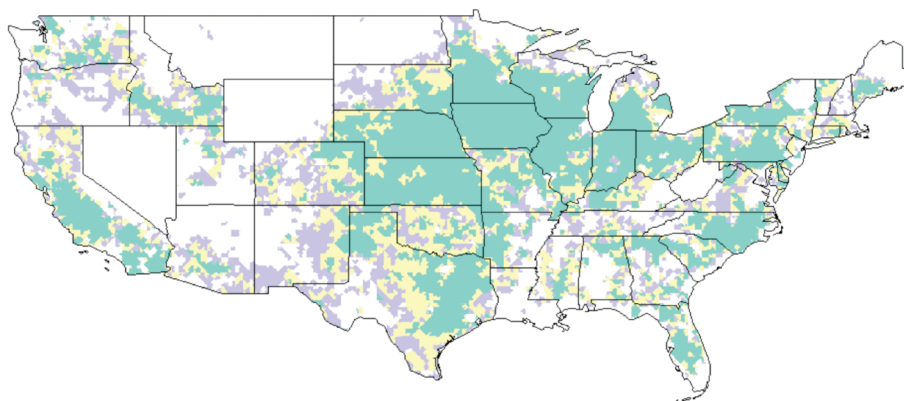
Digester Size	Available MW				Transport cost ($/kwh)				Capital Costs ($/kWh)	Total Electricity Cost ($/kWh)				Average Markup over Conventional Electricity
Cluster area (km²)	225	400	625	900	225	400	625	900		225	400	625	900	
1000kW	5755	1666	1287	882	0.06	0.07	0.08	0.10	0.09	0.15	0.16	0.17	0.18	1.6
500kW	82	179	462	429	0.06	0.07	0.08	0.10	0.11	0.17	0.18	0.19	0.20	2.0
250kW	46	85	213	180	0.06	0.07	0.08	0.10	0.14	0.20	0.21	0.22	0.23	2.3

Figure 1. Readily available manure resources can contribute over 11 000 MW of electricity generation potential. Each colored grid cell is included in a cluster less than 900 km² that can support an AD of a given capacity. Electricity cost for each cluster is based on AD capital costs and manure transportation costs. AD electricity generation is initially uncompetitive with conventional electricity but enters as the cost of conventional electricity rises.

determined by two factors: capital costs and transportation costs. ADs exhibit capital cost trends similar to other energy generation technologies: larger, centralized units are less expensive to operate per unit of energy produced.[38] Data collected by EPA AgSTAR on generator capacity and capital costs exhibit a power law relationship ($r^2 = 0.911$).[39] We assumed that each system had a postdigestion solids separation system and hydrogen sulfide (H_2S) treatment at an added cost of 9.5% of capital costs.[39] Although centralized ADs might be less expensive to operate, there are additional logistical and coordination factors that need to be considered for optimal day-to-day management. There are currently more centralized ADs outside the U.S.[8,40,41]

As AD size increases, the amount of manure needed to supply the generator increases proportionally. Large AD systems often require manure inputs from several farms in order to take advantage of lower capital costs per kWh for larger generator systems. We assumed that the manure input from multiple sources was optimized for total solid content, pH, and other physical characteristics important to the digestion process. The cost of hauling large amounts of manure can be a significant portion of the final LCOE. In this study, we represent the trade-off between low capital cost with high transportation cost of larger systems, and high capital cost with low transportation cost of smaller systems, by including 1000, 500, and 250 kW ADs and spatially grouping manure resources according to system size. For each system, we assumed that 50% of the manure was available on-site, while the other half was transported via truck.[42] We further assumed that biogas was combusted on-site at 40% thermodynamic efficiency, and the electricity generated was sold to a utility at market prices averaged across users and states.[43,44] Waste heat collected from the generator was used to maintain the digester within the mesophilic temperature range (~38 °C). We assumed that digested manure was used as a fertilizer substitute, but not given an economic value. LCOE values for each digester

size were computed using the methods described in ref 12 with operations and maintenance assumed to be 3% of capital costs[45,46] (Table S2).

Manure availability was estimated using spatially explicit maps of livestock density, manure production and management parameters, and identification of areas with high manure densities. Gridded densities of cattle, pigs, and poultry available at 0.05° spatial resolution (~5 km) adjusted to match FAOSTAT 2005 national totals for the U.S. were used to estimate livestock populations.[13] Reference 14 provided state-level parameters on the excretion rate of volatile solids, maximum methane producing capacity, and typical animal mass needed to calculate methane production for dairy cattle, beef cattle, swine, and poultry in each state. The U.S. Department of Agriculture National Agricultural Statistics Service QuickStats database[47] provided a breakdown of state swine and poultry data by animal type, while the Cattle Enteric Fermentation Model[48] provided the distribution of cattle types. It was assumed that all manure was available for digestion, except manure from animals managed in pastured systems, as manure collection would be uneconomical under current conditions. Given these data, statewide coefficients for methane production potential were computed for each livestock group over the contiguous U.S. To determine the manure input for a typical AD, the proportion of potential methane for each livestock type was used to compute the percentage of manure input into a typical digester. Using ref 14 manure management data, average methane emissions from livestock manure not diverted to an AD were calculated as the potential project offset value.

To assess the full LCOE of ADs, costs for digesters that transport manure from off-site were estimated. Given the gridded methane production potential, clusters were identified that met the minimum amount of methane needed for a given digester size and were contained in the smallest number of contiguous grid

cells. The ArcGIS Spatial Order tool constructed a Peano curve over the input data set to quantify the proximity of a given cell to its neighbors. Next, the ArcGIS Collocate tool grouped points based on the Spatial Order value until a specified threshold of methane production potential was met. Clusters of grid cells less than 900 km^2 in area were identified as areas compact enough to support an AD without excessive manure hauling costs. Remaining clusters were separated into groupings less than 225, 400, 625, and 900 km^2, and it was assumed that each cluster was square and manure densities were higher in cells closer to the central cell (where the AD would be located). Transport distances were calculated by summing the distance of every cell to the central cell. Transport costs for each cluster size were computed with distance-cost hauling relationships from refs 40 and 49.
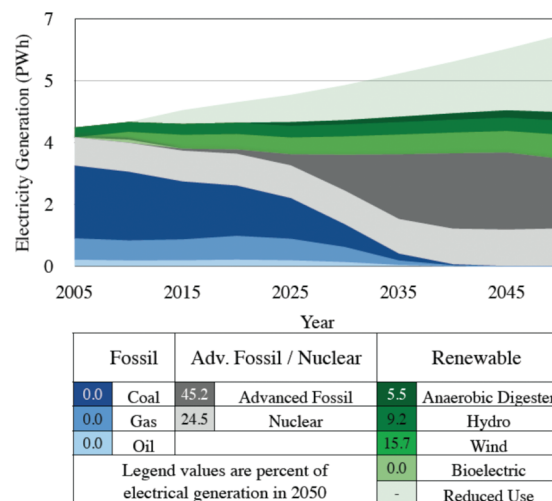
We identified three potential AD sizes based on clusters of available manure. We first identified clusters of grid cells that met the biogas requirements of a 1000 kW AD and were within a reasonable transportation distance (900 km^2), and the remaining cells were recursively analyzed to identify clusters that met the biogas production potential threshold for 500 and 250 kw ADs. For ADs of each size, we determined the LCOE by calculating the weighted average of AD clusters from each of the four transportation distance categories. ADs were represented in EPPA as alternative electricity generation technologies. We assumed that manure located near an AD of a particular size could not be used in an AD of a different size. This approach is suitable for determining the potential methane production potential across a region, but has limitations for siting a specific AD.

RESULTS

Manure Resource Availability. Over two billion cattle, swine and poultry in the U.S. produce manure that can be diverted to ADs to produce energy and then used as fertilizer. Our estimates show that manure collected and deposited in lagoons or pits currently has the potential to produce 11 000 megawatts (MW) of electricity, while manure from pastured animals could produce an additional 7000MW with modified collection practices. In our core scenarios, only manure collected and stored in lagoons or pits, and not pasture manure, is available for use in ADs. The greatest density of manure available for ADs is located in the Southeast, Midwest, and Western regions, and 14% of electricity demand in Iowa and Nebraska could potentially be met by ADs. (Figure 1, Table S1).

Economies of scale for ADs, and variable distances between manure sources and ADs, result in a range of generation costs for electricity from manure. We first identified three potential AD sizes based on manure density: 1000, 500, and 250 kW. We estimate that, ignoring transport costs, a 1000 kW AD is able to produce electricity at $0.086/kWh, while a 250 kW AD is 58% more expensive at $0.136/kWh. Electricity from a 500 kW AD is $0.107/kWh (Table S2). The cost to transport manure ranges from 30 to 53% of total electricity cost (capital + transportation cost), based on digester size and transportation distance. Transportation costs are $0.060/kWh for the smallest (225 km^2) and $0.096 for the largest (900km^2) clusters. Total electricity costs range from $0.128/kWh to $0.204/kWh, which is 1.52 to 2.44 times the cost of conventional electricity in the base year (2004) of our modeling framework.

**Carbon Prices, Anaerobic Digesters, and Economic Welfare.** Electricity from ADs competes with electricity from

Fossil		Adv. Fossil / Nuclear		Renewable	
0.0	Coal	45.2	Advanced Fossil	5.5	Anaerobic Digester
0.0	Gas	24.5	Nuclear	9.2	Hydro
0.0	Oil			15.7	Wind
Legend values are percent of				0.0	Bioelectric
electrical generation in 2050				-	Reduced Use

Figure 2. Simulated U.S. electricity generation 2005−2050 under a climate policy. Electricity generation under reference and climate policy without digesters are shown in Figure S2. Note: Advanced fossil includes natural gas combined cycle (NGCC), NGCC with sequestration, integrated gasification with combined cycle and sequestration, and wind with gas backup.

traditional sources based on generation costs. Under a climate policy that includes emissions from all sectors, electricity from fossil fuels becomes more expensive, and renewable and low-carbon electricity sources become more competitive. We consider a policy where between 2010 and 2050 the emissions cap is progressively reduced. Under the cap, the price per tonne of emissions increases to $316/tCO$_2$e (Figure 3a, Table S3) by 2050. This CO$_2$e price is much higher than prices currently observed in the E.U., but is consistent with other studies that consider emission limits that decrease over time.[50] CO$_2$e prices increase faster in the later years of the scenario, as more costly emission reductions are put into place. There is a sharp increase in the CO$_2$e price after 2045, as prior to this date the cap is largely met by switching electricity generation from coal to gas, but more radical measures are required to meet the cap after this date. The availability of ADs reduces CO$_2$e prices by $42 in 2050 relative to when ADs are not available, since ADs are able to produce energy less expensively than other low-carbon energy technologies and reduce agricultural methane emissions. By 2050, relative to a scenario with climate policy without ADs, ADs displace electricity from natural gas combined cycle (0.1 petawatt-hours, PWh) and wind (0.03 PWh) in 2050.

Under the climate policy, ADs are first introduced in 2025 when the price of CO$_2$e is $76/tonne and electricity is $0.15/kWh. In the first year ADs are economically available, assuming that potential AD electricity generation is maximized, they produce 0.1 PWh of electricity, which is 2.6% of national electricity generation. In 2050, ADs contribute 0.24 PWh of electricity, or 5.5% of national generation (Figure 2, Figure S2). This increase is mainly driven by the expansion of the livestock sector, but the introduction of more costly AD electricity generation as the price of electricity increases also plays a role. Compared to the climate policy scenario without ADs, the livestock sector grows faster when ADs are available, as increased profits from electricity sales and methane mitigation credits are realized.

As carbon prices rise, the cost to produce electricity from ADs becomes competitive with other electricity generating technologies

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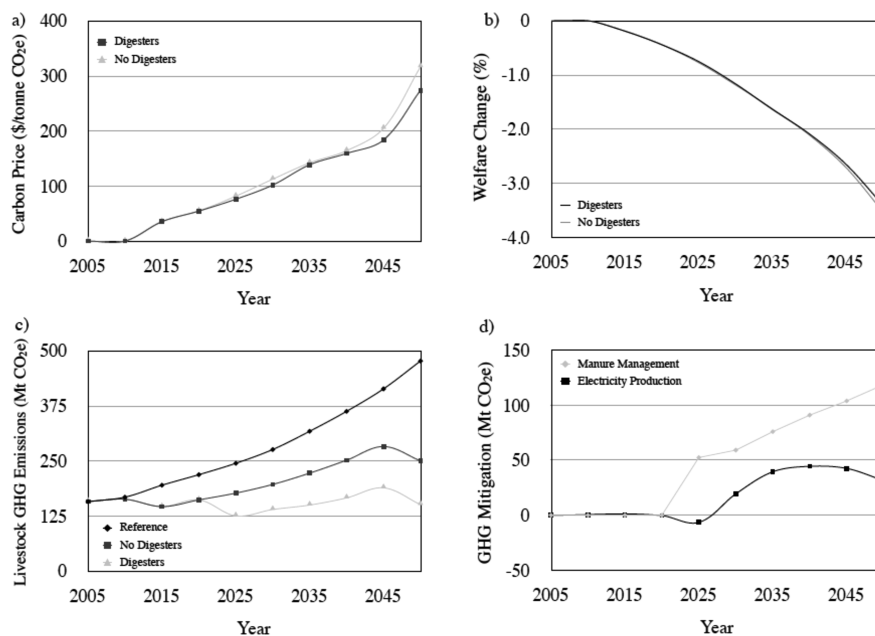
Figure 3. Changes in reference and policy scenarios until 2050 for (a) carbon prices, (b) economic welfare, (c) livestock greenhouse gas emissions, and (d) greenhouse gas mitigation (there is a net increase in GHGs from electricity production between 2020 and 2025 when ADs displace expensive, low-carbon).

and AD market penetration increases. The least expensive electricity is available from 1000 kW ADs, which enter in 2025. Further increases in the CO_2e price are required before smaller digesters become competitive. Electricity production from 500 kW and 250 kW begins in, respectively, 2035 and 2040.

Changes in consumer welfare, measured as equivalent variation changes in annual income, are often used as an indicator to measure the economic effects of a policy.[51] Not accounting for climate benefits, welfare under climate policy (without ADs) decreased by 3.5% relative to the reference scenario in 2050 (Figure 3b). When ADs were included, welfare increased by 0.2% ($33 billion), as they provided an additional mitigation option. This indicator of consumer welfare measures only changes due to the cost of GHG mitigation, and does not take into account potential social and environmental benefits of implementing this technology. Although important, analysis of these benefits is beyond the scope of this study.

Greenhouse Gas Emissions. Manure collected and managed under anaerobic conditions releases methane, a potent GHG. By diverting the manure to ADs, an opportunity to capture and combust the methane is created. Mitigating these emissions enables livestock operations to sell emissions permits, thereby increasing the economic viability of the projects. By 2050, ADs are able to mitigate 151 million metric tons (Mt) of CO_2e, mostly from methane abatement (Figure 3c, Table S3). In the reference scenario, the livestock sector emits 477 Mt CO_2e of methane in 2050, which is reduced to 250 Mt CO_2e under a climate policy without ADs as technologies are used to mitigate livestock emissions. Introducing ADs decreased livestock methane emission to 151 Mt CO_2e by 2050.

As electricity from ADs was introduced, electricity from other sources decreased. If electricity from ADs displaces an electricity generation technology with higher emissions intensity per unit of electricity, then additional GHGs are mitigated. In 2050, 31 Mt CO_2e of electricity emissions are displaced by digesters

(Figure 3d). This was mainly due to a decrease in electricity generation from natural gas-combined cycle (NGCC) and under the emissions cap, economy-wide emissions remained constant.

Interestingly, ADs do not necessarily displace high-carbon electricity production, such as coal. In our framework electricity generation sources compete with each other. The electricity mix is determined endogenously so as to minimize the cost of meeting the emissions cap. When ADs are available (and are profitable), ADs reduce the CO_2 price, which reduces the costs of electricity from high-carbon sources, relative to when ADs are not available.

■ DISCUSSION

Our results demonstrate the potential for climate policy to hasten the use of ADs, both to reduce GHG emissions from livestock and to produce renewable energy. By including ADs within an economic modeling framework, we illustrated the opportunity for a win—win scenario where, by providing incentives for the GHG benefits of digester operation, there are additional nonmarket benefits, even though they were not explicitly incentivized. This bundle of market and nonmarket benefits may increase the adoption rates of ADs.

Although capital costs are a major barrier to further introduction of ADs, there are opportunities to improve the efficiency of manure collection, processing, and subsequent biogas combustion that would increase the economic competitiveness of the technology. Most AD systems are currently installed at livestock operations with existing manure management strategies that may not be optimal for biogas extraction. Further research, development, and innovation is needed to design manure collection systems that simultaneously maximize biogas production and animal well-being, while minimizing the release of nutrients and GHGs. Siting ADs near energy-intensive industries would allow for better utilization of the waste heat from the combustion process.

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Although livestock that spend a majority of their time on pasture were excluded from our core scenarios, financial incentives to produce biogas may spur development of pasture-based manure collection systems that allow for both grazing and manure collection. These systems would realize both the environmental and animal welfare benefits of pasturing animals, and the economic benefits of biogas production.

The assumptions and core data that are the backbone of EPPA are routinely updated to the latest state of the science (SI and refs 4 and 31. While we parameterized the model with values from the literature, and conducted sensitivity analyses, many social, economic, and environmental trends cannot be modeled with certainty far into the future. We assumed that there were no major changes in consumer preferences, but as we move into an increasingly energy and resource constrained future, these assumptions may be optimistic. Therefore, less manure may be available for ADs in the future than in our estimates. Additionally, concern over environmental and health impacts of meat consumption may also reduce future livestock production.[52,53]

Although we only considered livestock manure as an input to ADs, they can also break down many other forms of organic wastes to produce biogas, often at higher rates of biogas production per unit input than manure, as manure has already been digested by the animal.[54] Co-digesting other organic materials with manure can relieve pressure on other waste processing facilities and increase biogas production without greatly increasing the size and capital costs of the digester.[55] Several municipalities already collect household food scraps and waste grease, and digestion of these materials could increase AD profitability and further reduce the environmental impact of waste disposal.[56]

We derived model parameters for AD GHG mitigation and electricity generation from published sources, but we acknowledge that there remains uncertainty about methane emission rates from livestock under different management practices.[57] Even if methane credits increased by 30%, which we considered in a sensitivity analysis, electricity generated by ADs only increased by 0.003 PWh in this scenario, and 500 kW ADs became economical five years earlier (Table S6). Improved methods to measure GHG emissions from livestock, e.g. ref 58, will be needed to improve upon currently used generalized emissions models. Life cycle assessment is one tool that can be used to assess the release of GHGs and nutrients from a farm that can lead to implementing the most effective mitigation options.[58]

Even in the absence of a broad climate policy that prices carbon, there are other mechanisms to encourage installation of additional AD capacity. Several states have implemented renewable portfolio standards that have driven the adoption of alternative energy sources.[59] Germany uses a feed-in-tariff to guarantee competitive prices for energy produced from ADs, and is a global leader in biogas production.[54] California's low carbon fuel standard (LCFS) ranks transportation fuels by their life-cycle carbon intensity. For illustration, biogas from dairy ADs can be used as a transportation fuel if it undergoes upgrading and compression. It is then comparable to traditional compressed natural gas with one-fifth the carbon intensity because a credit is applied to the biogas owing to decreased methane emissions compared to traditional manure management techniques.[60] Some AD projects are intended to reduce other environmental impacts such as nutrient runoff, and GHG emissions may be a secondary concern.

ADs can provide energy for a single household, as seen in India and China,[6,7] or up to several thousand households such as in Toronto, Canada.[61] While the technology is scalable, decisions regarding sites, operations, and sources of digestable material are outside the context of this study. Our approach matched digester sizes (1000, 500, 250 kW) to resource density in order to minimize the capital investment and transportation costs per unit of energy generation. While this approximation is useful at a national level, each potential AD project will need to survey the availability and cost of manure and organic materials for codigestion to maximize the environmental and economic efficiency of the project.

Using a computable general equilibrium model in this context allows us to investigate the interactions among sectors, illustrated here in the novel linkages between agriculture and energy production. While economic welfare decreased across all scenarios relative to the reference, the climatic benefits were excluded from these values, mostly because such calculation will suffer from much greater uncertainty and lack of information than on the cost side. Additionally, there are few metrics to quantify nonclimatic environmental benefits from ADs and thus these were excluded from the analysis.[62] Caution should be used when applying the results of this study to a specific project, since they are estimated across the entire economy and the projected changes in welfare do not include all costs and benefits to society.

Many of the fuel sources used today have social and environmental impacts that are not accounted for in standard economic transactions. Similar externalities exist within the agricultural sector, which will increase as livestock operations expand. Implementing a climate policy that places a value on carbon will ease the transition from diverting livestock manure to ADs to provide energy. As the external costs of fossil fuel energy are realized throughout the economy, the environmental cobenefits of AD further increase the societal value of avoiding traditional manure management.

■ ASSOCIATED CONTENT

ⓢ Supporting Information. Expanded explanation of the economic modeling framework with a focus on the modifications made to the Emissions Prediction and Policy Analysis (EPPA) model, documentation of the methods used to integrate anaerobic digesters into an economic modeling framework, and an explanation of the alternative scenarios. Supporting tables and figures include model inputs and results from the modeling scenarios. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author
*E-mail: zaks@wisc.edu; phone: +1-248-444-3040.

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