Economic Viability of Bioenergy Production on Large Dairy Farms: An Assessment for New Mexico

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Executive Summary

This comprehensive report focuses on the innovative use of animal manure as a potential source of bioenergy, thereby addressing two major challenges facing large-scale dairy farms in New Mexico: manure management and greenhouse gas emissions. Large dairy farms in the state produce significant amounts of manure which can not only create logistical difficulties for livestock producers but also cause local-level environmental pollution and greenhouse gas emissions. Alternative manure management strategies therefore make an economic as well as environmental sense.

New Mexico has ranked number one in the country in the average stocking density of large dairy farms (i.e., dairy farms with 500 or more cows) since 2002 (Joshi & Wang, 2018; USDA, 2019). Dairy is the state's most important agricultural industry with the largest cash earnings. The dairy sector provides direct jobs to 6,909 people and contributes 6.7% of the state's gross domestic product, with an indirect economic impact of $4.2 billion and a direct economic impact of $2.2 billion (Hagevoort, 2023; IDFA, 2021).. Most of the large dairy farms in New Mexico are in five southeastern counties: Curry, Roosevelt, Chaves, Dona Ana, and Lea. These counties house roughly 90 percent of the state's 326,946 dairy cows (USDA, 2019). The number of milk cows has lately grown by 6 percent from 2012 to 2017, while the number of dairy farm operations fell by 5 percent, which speaks toward a trend of dairy farm consolidation (USDA, 2019). Large dairy farms now account for more than 99 percent of the statewide dairy cow inventory and hold a corresponding percentage of the dairy products market (USDA, 2019).

This report evaluates the bioenergy potential of these large dairy farms in New Mexico and assesses the viability of two alternative technologies (whether producing electricity or gas from manure) under four different scenarios (whether considering co-products and/or environmental

credits). The assessed manure management system encompasses an Anaerobic Digestion (AD) unit for raw biogas production, Combined Heat and Power (CHP) unit for electricity generation, Compressed Natural Gas (CNG) unit for gas refinement, fiber separation unit, and nutrient separation unit. Through comparative analysis, this report establishes that AD systems that produce electricity and valuable co-products like fiber and nutrients, and that also benefit from environmental credits, exhibit the highest profitability. The study further delves into the socio-economic aspects, analyzing the net social benefits of the AD system, which sometimes surpass the private benefits. Policymakers can play a vital role in encouraging the adoption of AD systems by providing financial incentives like tax breaks, subsidies, low-interest loans, and grants. However, the onus is not just on the government; altering the perception of AD systems from burdensome investments to profitable ventures is critical for their broader acceptance. As the report concludes, the success of any AD system hinges on the existence of a robust market for its co-products.

The key findings of this study are:

- The most optimal configuration for an Anaerobic Digestion (AD) system in New Mexican dairy farms was identified as the Combined Heat and Power (CHP) system with fiber and nutrient separation, offering significant financial and environmental benefits. The marginal NPV for an average farm with 3,187 cows is $5,077 per cow, showing a promising gross margin of around 48%.
- Revenue from Renewable Energy Certificates (RECs) and nutrient separation were found to contribute the most to overall revenue, 43.68% and 31.31% respectively. This insight emphasizes the importance of maintaining all revenue streams for portfolio diversification and risk management, even those contributing less.

- AD systems bring substantial external benefits including greenhouse gas emission savings and health benefits from reduced pollution. The marginal external benefits ranged from \$6,171 to \$21,978 per cow, suggesting the positive externality of AD systems may not be captured fully by private benefits alone.
- The study challenged the perception of AD systems as regulatory burdens, proposing instead that in some cases, AD systems can generate higher revenues than the dairy system itself.
- The potential implementation of the Low Carbon Fuel Standard (LCFS) in New Mexico, which would not only align with the state's climate goals but could also provide farmers with additional revenue and societal health benefits, is a significant finding. The feasibility of this requires further investigation, particularly given the challenges associated with applying LCFS to CNG generated in the state.

In conclusion, our comprehensive assessment reveals a promising potential for the implementation of Anaerobic Digestion (AD) systems in New Mexican dairy farms, with the Combined Heat and Power (CHP) system with fiber and nutrient separation emerging as the most optimal configuration. Such systems not only offer substantial financial benefits with significant returns on investment but also contribute meaningful environmental benefits through greenhouse gas emission savings and reduced pollution. Importantly, our study reframes the perception of AD systems as burdensome regulatory obligations, suggesting instead they can be a lucrative revenue source, often exceeding the profits from the dairy operations themselves. Finally, we identify the potential for the implementation of the Low Carbon Fuel Standard (LCFS) in New Mexico. Though not without its challenges, its introduction could further enhance the revenue for farmers, aid in achieving the state's climate goals, and bring broader societal health benefits. Future research could focus on the further optimization of AD systems' locations and configurations, ultimately leading to a more sustainable and profitable dairy industry in New Mexico.

1. Introduction

Cattles have been domesticated for over 9000 years, primarily for their milk (Evershed et al., 2008). For much of this lengthy era, cattle rearing, and milk production practices remained relatively unchanged. However, the mid-twentieth century heralded a period of substantial technological advancement, catalyzing transformative changes within the industry. On larger farms, milking and feeding units started to mirror industrial manufacturing processes rather than traditional agricultural activities. Milk preservation techniques such as pasteurization and refrigeration significantly bolstered the dairy industry's growth, serving the nutritional needs of an expanding global population. However, this expansion led to an unprecedented increase in manure production. While traditional methods repurposed manure as soil amendment, firewood, flooring, plastering, and construction material, the sheer volume of manure generated daily by large farms rendered these traditional methods untenable. To address this challenge, a series of innovative and technologically advanced methods were developed over time. One notable approach involves the production of bioenergy from manure and animal waste—a solution that has proven to be both economically viable and environmentally sustainable. Such novel techniques offer encouraging solutions to manage the significant quantities of manure generated by modern dairy operations.

The large-scale farms also known as Concentrated Animal Feeding Operations (CAFOs) produce huge amounts of animal wastes deteriorating the environmental quality, harming public health, and impacting the socioeconomic conditions of surrounding residents. Pollution of the air, water and soil is the primary environmental damage of these farms. Surface runoffs or nutrients that seep into ground and surface water sources can pollute the water (Burkholder et al., 2007). Such contamination can cause nutrient overload, mainly phosphates and nitrogen, which can promote the growth of harmful algal blooms (Heisler et al., 2008). Consumption of cyanotoxin from algae and nutrient-contaminated water can lead to various respiratory diseases, gastrointestinal disorders, skin irritation, and blue-baby syndrome (Hribar, 2010). The algal blooms can also deplete oxygen levels in the water bodies affecting the diversity and abundance of aquatic life (Spellman & Whiting, 2007). Communities that rely on water and aquatic ecosystems in these bodies of water are among the worst hit. Similarly, the air born emissions from CAFOs can inflict various cardiovascular and respiratory illnesses. Additionally, residents living near CAFOs may experience adverse effects on their mental health and overall quality of life (Baliatsas et al., 2020; Schulze et al., 2011). Unregulated manure application can also disrupt the nutrient balance in soil, causing soil erosion and reducing soil fertility. Pathogens, pests, and parasites such as E. coli and Salmonella can infect humans or infest human dwellings through contaminated air, water, food, and other agricultural articles (Hribar, 2010). The secondary transformation of pollutants can trigger acid rain and ozone formation, harming plant life, corroding monuments and man-made structures, and obstructing economic growth and human progress. Furthermore, disadvantaged demographic groups are more likely to experience the disproportionate harmful impacts from the mismanagement of manure and animal waste.

The livestock industry is also a significant contributor to greenhouse gas (GHG) emissions, primarily methane and nitrous oxides, with higher radiative warming potentials than carbon dioxide (Bellarby et al., 2013). Radiative warming potential denotes the ability of a substance to accelerate climate change over a specific period. Methane and nitrous oxides possess radiative warming potentials 28 and 265 times higher than carbon dioxide over a period of 100 years, respectively (Pachauri et al., 2014). In 2021, the livestock industry was responsible for nearly 36% of the total methane emission in the US (US EPA, 2023a). Among these, 26.8% emanated from enteric fermentation, and 9.1% from manure management. This study primarily concentrates on curbing emissions from manure storage and handling, as these processes are more amenable to engineering and control interventions. In 2021, methane emissions from manure management were gauged at 66.0 million metric tons (MMT) of carbon dioxide equivalents (CO2e), marking a 69% escalation from the 1990 level of 39.0 MMT CO2e (US EPA, 2023a). The average annual increment in emissions over this period was 0.8 MMT CO2e. This surge in emissions can be attributed to the heightened production and application of swine and dairy cow manure, with emissions from these sources inflating by 38% and 124%, respectively (US EPA, 2023a).

Stakeholders, including farmers and policymakers, are actively exploring innovative strategies for managing manure that can simultaneously promote environmental conservation and stimulate revenue generation. Composting, compaction and coverage, temperature control, anaerobic digestion, and periodic removal of slurries have been identified as primary methods to curtail GHG emissions from manure (Leip et al., 2010). Of these, anaerobic digestion (AD) alone can diminish methane emissions by 25-80%, given effective capture and combustion are in place, and field application of nutrient-stripped, digested slurry can yield a 30-50% reduction in nitrous oxide emissions (Clemens et al., 2006; Sommer et al., 2000). AD constitutes a natural process wherein microorganisms decompose organic matter in the absence of oxygen, yielding biogas—a concoction of methane and carbon dioxide (O'Connor et al., 2020). A commercial AD system employs an engineered approach and a controlled design to process organic biodegradable matter within air-tight reactor tanks, thereby producing biogas (Vögeli et al., 2014).

Auxiliary technologies can bolster the economic and environmental benefits of AD systems. These include heat and electricity production, biogas upgrading, solid-liquid separation, digestate treatment, nutrient recovery, microalgae cultivation, and pre-treatment technologies. The integration of these technologies can facilitate direct revenue generation from the sales of gas, electricity, fiber, and nutrients. They can also engender secondary benefits such as job creation, reduced waste disposal costs, and diminished reliance on chemical fertilizers. Non-monetary benefits include decreased dependency on fossil fuels, improved soil nutrient balance, reduced odors, pathogens, and pests, and lessened ecosystem damages (Yiridoe et al., 2009). In developing nations, AD systems can further alleviate deforestation and exposure to indoor air pollutants (Al Seadi et al., 2008). The integration of household organic wastes into the AD system can also prolong the lifespan of landfills (Vögeli et al., 2014). Despite these benefits, high initial capital costs and the marketability of co-products still pose barriers to the widespread adoption of the AD technology (Astill and Shumway, 2016).

New Mexico, a state prominent in dairy production, has witnessed remarkable growth in this sector over the past few decades. The industry ranks as the top revenue generator among all agricultural commodities. The state's annual milk production averages 7.8 billion pounds, generating $1.3 billion in total sales (USDA, 2019). The state also has the highest average number of cows per large dairy farm in the nation (USDA, 2019). These dairy farms, among the nation's most expansive and productive, are geographically clustered within a relatively compact region. Over 90% of the state's 326,946 cows are located in the five southern counties of Chaves, Curry, Roosevelt, Dona Ana, and Lea (USDA, 2019).

This study's objective is to evaluate the bioenergy potential of large dairy farms in New Mexico and assess the viability of various configurations of AD systems using comparative cost-benefit analysis. Our analysis embraces a continuous range of farm sizes numbering up to 25,000. To dissect the financial potential of the various technological combinations under consideration, we invoke the economic concept of Net Present Value (NPV). We also critically evaluate the profitability of AD systems, contrasting those that rely on the sale of co-products alone against those that also secure environmental credits. Furthermore, our study ventures into a stochastic evaluation of the impact of carbon credits on the viability of AD systems, reflecting the inherent uncertainty surrounding these environmental instruments. A sensitivity analysis is also undertaken to gauge the resilience of revenue streams against parameter fluctuations. Ultimately, we incorporate the non-market benefits of AD systems into our analysis, illustrating how acknowledging and internalizing these benefits can further justify the feasibility of AD systems.

Our exploration contributes to the expanding corpus of literature on economic and environmental evaluations of manure management, inextricably intertwined with bioenergy production, specifically within arid land regions and the broader context of the US Southwest. We expand the analytical scope to encompass alternative technology components and novel revenue streams, thereby furnishing fresh empirical evidence on the economic viability of AD systems within these regions. We also update earlier cost and revenue functions, rendering them more pertinent for future investigations of analogous systems in other parts of the country. This study is the first to monetize the health benefits of AD systems, providing a comprehensive assessment of the non-market benefits of this technology. Our findings present insights for policymakers and potential investors who harbor interest in installing AD systems on CAFOs in arid regions and elsewhere, thereby significantly advancing the discourse in this field.

2. Background

The process of AD, a natural phenomenon manifesting in environments such as swamps and the gastro-intestinal tracts of ruminants, has been understood and harnessed since ancient times (Vögeli et al., 2014). The Assyrians were the pioneers in leveraging biogas as early as the 10th century, with the Persians following suit in the 16th century (Müller, 2007). Italian physicist Volta documented the process of methane generation from organic matter in 1776, instigating further exploration into the connection between organic matter decomposition and methane production through the 17th to 19th centuries (US EPA, 2020a). The first commercial AD/biogas plant was established in Bombay, India in 1859, followed by its use in England in 1895 to illuminate streetlamps (Wilkinson, 2011). The advent of this process began in open-air anaerobic ponds but was later refined with the introduction of enclosed tanks and heating/mixing apparatus. Despite the ongoing research and development of AD systems in the Western world, the prevalent low prices of coal and petroleum acted as deterrents to its widespread adoption. However, fuel shortages during WWII and the 1970s prompted countries with limited fossil fuel reserves to invest in micro-level AD systems, utilizing human, animal, and kitchen waste. Anecdotal evidence suggests an excess of 5 million operational AD/biogas systems globally, mostly on a single-family home scale. The global biogas electricity production capacity, which was less than 2.5 GW in 2000, had grown to over 21.5 GW by 2021 (IRENA, 2022).

Europe is the global leader in biogas electricity production, contributing over 14 GW to the total of 21.5 GW generated globally (IRENA, 2022). This significant surge in European biogas production can be attributed to the favorable support schemes enacted by several European Union (EU) member states. As of 2015, the European continent boasted over 17,400 biogas plants, with Germany housing an estimated 8,000 commercial digesters (Scarlat et al., 2018; US EPA, 2020a). Among EU countries, Denmark and the Czech Republic lead in per capital biogas production, while Sweden, Norway and France lag (*Database - Eurostat*, 2023). The majority of EU-produced biogas is harnessed for heat and electricity generation, with countries such as Germany, Italy, Denmark, the Czech Republic, and France leveraging agricultural waste for bioenergy, while Sweden, Norway, Switzerland, and Finland utilize municipal wastes (Gustafsson & Anderberg, 2022; Scarlat et al., 2018). In Sweden, Norway, and Finland, biogas is predominantly utilized as a transportation fuel (Gustafsson & Anderberg, 2022). The prime motivator for biogas uses in Europe is energy security, closely followed by environmental and sustainability concerns.

Contrarily, low to middle-income nations in Asia and Africa have gravitated towards small-scale biogas systems that capitalize on locally sourced, affordable materials. These systems typically fulfill the basic energy requirements of single households or small neighborhoods, though with lower yields and a higher percentage of impurities. China leads Asia in electricity generation from biogas plants, with an installed capacity of 1.7 gigawatts out of a total 2.9 gigawatts capacity of the whole continent (IRENA, 2022). A total of 43 million biogas users were counted in China in 2013 (Giwa et al., 2020). As a result of government subsidies, India had around five million household biodigesters in 2014 (Mittal et al., 2018; Sikora, 2021). Meanwhile, Africa exhibits a relatively nascent stage of AD system adoption with a total capacity of 0.05 gigawatts in 2021 (IRENA, 2022). However, the continent has seen a fivefold increase in total capacity over the past decade, led predominantly by South Africa and Egypt. In Latin America, numerous agricultural waste projects have been implemented, and urban areas extract landfill gas, resulting in a total bioelectricity production capacity of 0.6 gigawatts in 2021 (IRENA, 2022). Particularly in energy-scarce, remote regions, small-scale biogas systems offer an invaluable alternative to traditional energy sources like firewood, which carry significant health risks. Thus, the utility of AD systems extends beyond their immediate energy generation capabilities, providing a sustainable and health-conscious energy solution for communities worldwide.

In the United States, the predominant sources of biogas production are landfills and wastewater treatment plants that use anaerobic digesters. Recently, there has been a surge in interest towards the utilization of dairy and swine manure for energy production. According to the American Biogas

Council (2023), there are 1,269 water resource recovery facilities and an additional 68 independent systems within the US that utilize anaerobic digesters for processing food waste. The EPA further documents the operation of 331 farm-based digesters (US EPA, 2022) along with 532 landfill gas projects (US EPA, 2023b). Biogas is mainly harnessed in engine-generators or boilers to generate electricity and heat, though there is an emergent trend towards refining biogas into biomethane (IEA, 2020).

However, the expansion of AD systems in the United States has been somewhat hampered by the relatively high labor and capital costs associated with these systems, coupled with their lower energy efficiency in comparison to conventional energy sources such as grid-connected electricity and fossil fuels. Nevertheless, the increasing impetus from governmental incentives and a growing pro-environmental ethos presage a brighter future for the adoption of AD systems.

According to AgSTAR's calculations, over 8,000 large dairy and hog operations in the US could potentially generate nearly 16 million megawatt-hours (MWh) of energy annually and displace approximately 2,010 megawatts (MWs) of fossil fuel-fired generation through biogas recovery from AD systems (US EPA, 2022). Not all livestock farms may be ideal for bioenergy production therefore the EPA has identified 2,704 candidate farms for bioenergy production across the US based on the availability of organic waste, established manure management system, available space for infrastructure, access to utilities and a commitment to sustainable practices. These 2,704 candidate farms alone could contribute nearly 60% or 9.24 million MWhs of energy equivalent to 1,172 MWs of fossil-fuel-fired generation. California leads the nation in terms of the number of candidate farms for bioelectricity production from dairy manure, followed by Idaho, Wisconsin, Texas, and New Mexico. In New Mexico specifically, there are 88 candidate farms that possess a methane emission reduction potential of 8.3 million tons and a methane production potential of

6.26 billion cubic feet per year (US EPA, 2018). If all 144 potential biogas systems (including wastewater, landfills, and manure management) were built in New Mexico, it could generate estimated $432 million in capital investments, create 3,599 construction jobs and 239 permanent positions, and reduce GHG emissions equivalent to growing 606 million coniferous tree saplings for 10 years (American Biogas Council, 2023). Currently, there are only 16 biogas systems in New Mexico, comprising 12 wastewater treatment systems, three landfill systems, and one system for manure management.

Anaerobic digesters are considered as one of the 10 building blocks to reduce GHG emissions and generate clean and renewable energy. Their role aligns with 12 of the 17 Sustainable Development Goals, including the augmentation of renewable energy, mitigation of climate change, amelioration of waste management, and employment creation, all of which are buttressed by biogas generation (Obaideen et al., 2022). However, the financial viability of these systems is often challenged by steep initial costs (Bishop & Shumway, 2009; DeVuyst et al., 2011; Kruger et al., 2008; Wang et al., 2011). Various government grants such as Conservation Innovation Grants, and the Environmental Quality Improvement Program, can help to defray the initial capital outlay of these projects (Cowley & Brorsen, 2018).

Renewable energy policies can also positively influence the adoption of AD systems. State mandates such as renewable portfolio standards (RPS), interconnection standards, net metering, feed-in tariffs, and financial incentives can all serve to stimulate renewable energy generation. A suite of financial tools, including grants, loans, rebates, and tax credits, further support farmers in this endeavor (US EPA, 2014). Federal tax incentives, including Renewable Electricity Production Tax Credit, the Investment Tax Credit, the Residential Energy Credit, and the Modified Accelerated Cost-Recovery System, have a particularly profound impact. Research indicates that these financial incentives can determine the success or failure of an AD system, and favorable policies have catalyzed a proliferation of AD systems in regions with supportive regulatory frameworks and renewable energy incentives (Cowley & Brorsen, 2018).

The advent of carbon credit markets presents a unique opportunity for biogas producers, and dairy farmers who invest in methane capture technologies such as anaerobic digesters. Carbon credits are tradable instruments that allow entities to offset emissions that are difficult to mitigate by investing in initiatives that prevent or eliminate emissions elsewhere. These markets can have two forms: compliance and voluntary. Compliance markets are utilized by legal jurisdictions to satisfy their legal obligations, while voluntary carbon credit markets are used by private parties to meet their emission reduction goals (Blaufelder et al., 2020).

Regulatory measures like Renewable Portfolio Standards (RPS) incentivize the use of renewable sources for electricity generation. These policies mandate or encourage utility providers to supply a predetermined share of electricity from eligible renewable resources. Most states have instituted their own RPS programs, which incorporate a renewable electricity certificate (REC) trading system to curtail the cost of compliance (US EPA, 2015). Net metering is another policy that allows electric utility customers to install qualifying renewable energy systems on their properties and connect them to an electric utility's distribution system. Feed-in tariffs provide special rates for purchasing electricity from certain types of renewable energy systems, while interconnection standards establish uniform processes and technical requirements for connecting renewable energy sources to the electric grid.

Biogas can also be processed and sold as biofuels or alternatives vehicle fuels which are regulated and incentivized by federal and state level policies. The Low Carbon Fuel Standard (LCFS), for instance, aims to reduce the carbon intensity of transportation fuels by setting a target carbon intensity value for fuel suppliers (US EPA, 2020b). To reduce compliance costs with this standard, the LCFS uses a REC trading system, similar to cap and trade for the transportation sector Akin to the cap-and-trade system for the transportation sector, the LCFS utilizes a REC trading system to mitigate compliance costs. The renewable identification numbers (RINs) system is another incentive mechanism that monitors the production, use, and trading of biodiesel and other renewable fuels. Before 2014, biogas derived from AD could only qualify for D3 RINs when used as a transportation fuel in the form of liquefied natural gas or compressed natural gas (US EPA, 2020b). In 2014, the EPA expanded this pathway to specify Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG) as the fuel and biogas as the feedstock, enabling fuels derived from landfill biogas to qualify for cellulosic biofuel (D3) (US EPA, 2020c). These policies ensure that renewable energy producers are duly compensated for their efforts, and any surplus electricity generated can be credited for future use. These interconnections between dairy farming, bioenergy production, and carbon credit markets open unique avenues for exploring manure management strategies that bolster economic development while mitigating GHG emissions.

The state of New Mexico exemplifies a robust environmental stance and proactive renewable energy assistance programs. The state aims to reduce GHG emissions by 45% below 2005 levels by 2030 and achieve net-zero emissions by 2050. New Mexico Energy Transition Act mandates renewable energy standards for investor-owned utilities and rural electric cooperatives. Recognizing anaerobic digesters as a zero-carbon resource, the Act supports New Mexico in reaching its clean energy targets. Anaerobic biodigesters that meet the state's renewable energy requirements are eligible to claim RECs.

This study aims to evaluate the viability of AD systems for large dairy farms by comprehensively assessing the cost and revenue parameters of various technology combinations and environmental incentive regimes. It considers dairy farms with herd sizes up to 25,000 cows and compares the NPVs of two technological alternatives. We also perform a stochastic assessment to evaluate the impact of uncertainties in carbon credit prices on the viability of AD systems. A sensitivity analysis is also undertaken to gauge the resilience of revenue streams against parameter fluctuations. Ultimately, we incorporate the non-market benefits of AD systems into our analysis, illustrating how acknowledging and internalizing these benefits can amplify project profitability. By providing valuable insights for policymakers and investors keen on promoting the widespread adoption of AD systems in arid regions and beyond, this study fills a gap in the literature on economic and environmental assessments of manure management coupled with bioenergy production.

3. Methodology

This study assesses the economic feasibility of integrated AD systems, focusing on their capacity to generate revenue for farmers and their potential to mitigate environmental externalities. To evaluate the impact of herd size on the net present value (NPV) of the net benefit of an AD system over its lifetime, we considered dairy farms with herd sizes up to 25,000 cows. The cost and revenue functions are linear functions of herd sizes therefore the NPV changes almost linearly with the increase in the farm size.

3.1 Components of an AD System

Anaerobic digesters are available in various configurations and types. They may be stand-alone systems that solely produce electricity or biogas as the primary product, or they may be integrated systems using modular technology components to yield auxiliary co-products such as high-value fibers and nutrients, in addition to the primary product. Each technology component varies in terms of input and output and carries associated costs. Figure 1 provides a schematic representation of an integrated system that encompasses all five technological components, their associated co-products, potential environmental credits, and attainable external social benefits.

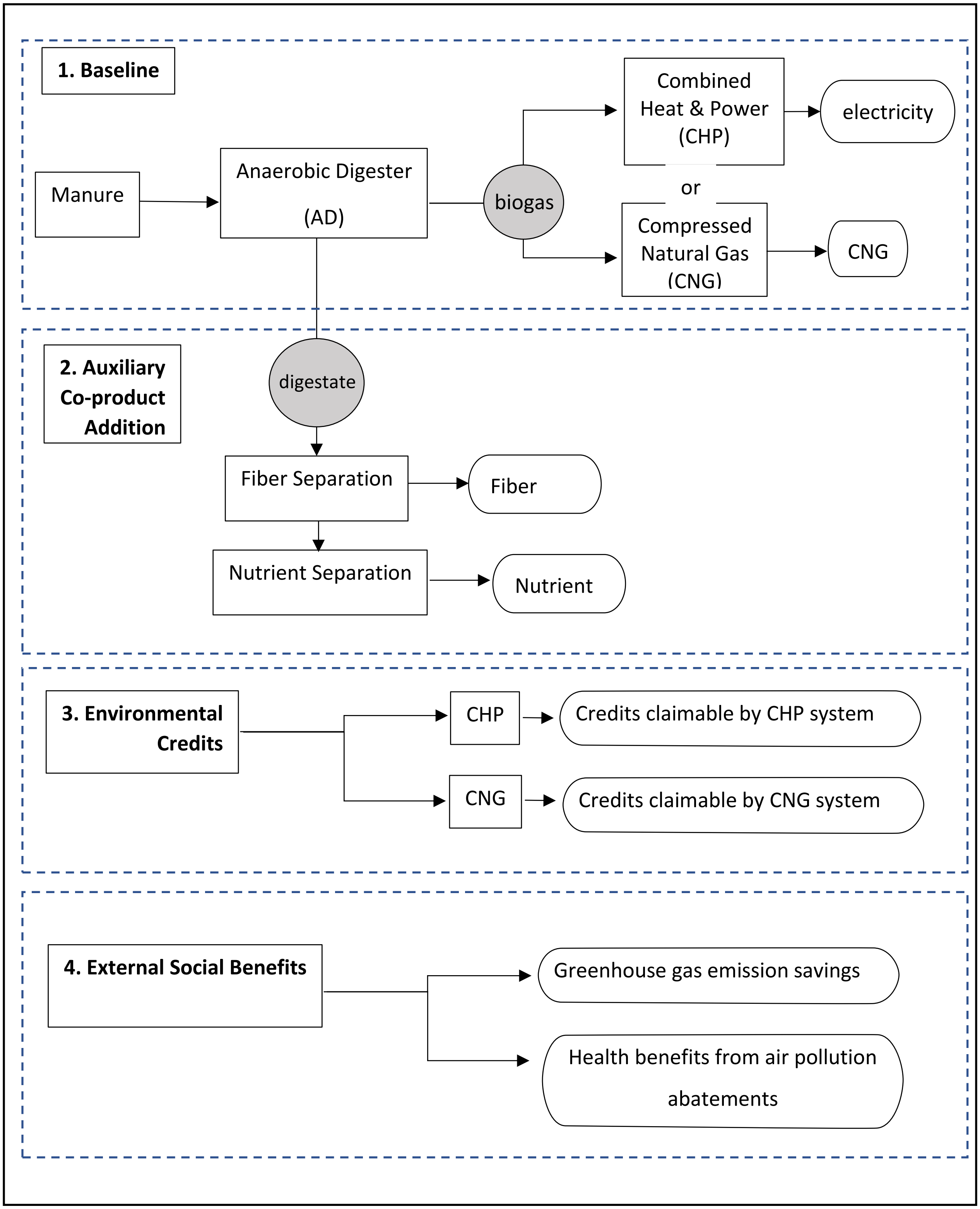


Figure 1: Schematic representation of an integrated AD system with technological components, environmental credits and external social benefits

i. Anaerobic digester (AD)

The AD unit serves as the base component of an AD system, converting organic solids into biogas and fiber through the agency of anaerobic bacteria. The resultant biogas and fiber, however, necessitate further processing through CHP or CNG units to make them marketable. In our study, we assume the use of a complete mix AD, with the biogas subsequently processed by either CHP or CNG units. As such, while the AD system incurs costs, it does not have an associated revenue function.

ii. Combined heat and power (CHP)

The CHP unit is a technology component which when combined with the AD unit, forms the basic functional AD system or base system. The CHP unit produces two co-products: heat and electricity. While the primary products of the CHP unit are electricity and heat, we only include the revenue generated from the electricity sales, and do not monetize the value of the heat produced. We also assume 100% of the generated electricity to be connected to the electric grid.

iii. Compressed natural gas (CNG)

CNG is another technology component that can be combined with the AD unit to form the basic functional AD system. The main product of this unit is natural gas, which is derived from the biogas being scrubbed of water and contaminants before its compression for delivery or utilization. CNG can serve as biofuel for transportation or as an energy source for heating and cooking in residential settings. While it is possible for AD system owners to connect their system to the national CNG pipeline, we do not take this into consideration due to the high cost of pipeline integration.

iv. Fiber separation (FS)

FS serves as an auxiliary component within the AD system, producing high-value fibers that can be sold under two different labels depending on the market preference and demand. Selling the fiber as a peat moss replacement enables charging higher prices, whereas selling it as a soil amendment results in lower price points. Although the system solely produces high-value fibers, we consider two alternative revenue functions, one for high-value fiber (peat moss replacement) and another for low-value fiber (soil amendment).

v. Nutrient Separation (NS)

The NS unit is another auxiliary component of an integrated AD system, producing high-value fertilizer products by separating phosphate and ammonia from the effluent. The NS unit requires a preceding fiber separation process to function effectively, as it relies on the separation of solid fiber from the effluent to ensure a smoother process. The NS unit generates revenue through the sales of high-value fertilizers, targeting specifically the agricultural industry where these nutrients can be applied directly into the field.

3.2 Cost, Revenue and Net Benefit

The capital cost and operation and maintenance (O&M) costs of the AD systems are calculated using equations (1) and (2). Similarly, the revenues and transactional costs of environmental acquisition are calculated using equations (3) and (4).

Capital cost:

$$C(x) = \begin{cases} v_1 x + f_1, & if\ x < \alpha \\ v_2 x + f_2, & if\ x \geq \alpha \end{cases} \tag{1}$$

Where, the capital cost function is a piecewise function dependent on the threshold size of the farm α. The farm size or the number of cows per farm is represented by x. The capital cost comprises both variable and fixed costs associated with a specific technology component. The variable costs tied to a particular technological component reflect expenses that change based on the farm size. Whereas the fixed costs encompass costs that stay constant regardless of the farm size within that cost structure.

For farm with a size less than α, the capital cost is calculated using the first cost function where v_1 is the variable cost and f_1 is the fixed cost. Similarly, for farms with size equal to or greater than α, the capital cost is determined by the second cost function where v_2 is the variable cost and f_2 is the fixed cost. This piecewise function allows for different cost structures depending on the size of the farm.

Operation and maintenance cost:

$$\Omega(x) = \begin{cases} w_1 x + g_1, & if\ x < \beta \\ w_2 x + g_2, & if\ x \geq \beta \end{cases} \tag{2}$$

The O&M cost function also exhibits a piecewise structure where, w_1 and g_1 represent the variable and fixed O&M costs of the first cost structure. Similarly, w_2 and g_2 represent the variable and fixed O&M costs of the second cost structure. β is the threshold size of the farm for O&M function.

Revenue:

$$R(x) = z_1 x\, p_1 + z_2 x\, p_2 \tag{3}$$

z_1 represents the marginal output of a product per cow tied to a particular technological component and p_1 represents the prevailing market price of this product. Some components of the AD system yield multiple products or yield products that command multiple prices in the market. Therefore, z_2 and p_2 represent the marginal output per cow and the price of the second product or alternative specifications for the same product depending on the situation.

The following equations show the revenues and transaction costs associated with the environmental credits:

Revenue:

$$R(x) = a_1 x \, p_3 \tag{4}$$

Transaction cost:

$$\xi(x) = a_2 x \, p_3 + b \tag{5}$$

Where,

a_1 and a_2 represent the variable component of the cost and revenue. p_3 represents the marginal price of the credit and b represents the fixed component of the cost where applicable.

The NPV of net benefits, a yardstick of profitability, carefully weighs the time value of money when comparing revenues and costs. To assess the economic viability of the anaerobic digestion system, a generalized NPV function was used. The function calculates the NPV of the net benefit of the project for a given farm size by considering the present value of the revenue stream and the present value of the operation and maintenance costs. The discount rate and project life form are integral components of the calculation. The NPV function was constructed using the following equation:

$$\lambda(x) = \sum_{t=0}^{T}\left(\frac{R(x)}{(1+r)^t}\right) - \sum_{t=0}^{T}\left(\frac{\Omega(x)}{(1+r)^t}\right) - C(x) \tag{6}$$

Where, r is the discount factor and T is the project lifetime. We assume that the salvage value of the project is zero. In general, the rule of thumbs for investment decision is to greenlight a project when the NPV exceeds zero. The NPV also serves as a reliable metric to compare the profitability of diverse technological alternatives. The greater the NPV, the more viable the project.

The assessment of costs, revenue, and NPV is contingent on the values ascribed to a gamut of parameters and variables. Table A1 in the appendix lists all the parameters and variables utilized in the appraisal of costs, revenue, and NPV.

3.3 Deterministic Scenario Analysis

We use a combination of four scenarios to assess and compare the viability of various AD system configurations using a fixed price for co-products and environmental credits. The primary goal of this assessment is to optimize the private net benefits, as measured by the NPV of AD operators.

Scenario 1 (Baseline):

The first scenario evaluates the NPVs of the base AD system, constituted of either AD+CHP or AD+CNG. These system's primary products are electricity (generated by CHP) and compressed natural gas (generated by CNG). This scenario does not consider the production of any co-products or the attribution of environmental credits. For subsequent analysis, the AD+CHP and AD+CNG configurations are referred to as CHP system or CNG system, respectively, and serve as the basis of comparison for alternative technology components.

Scenario 2 (Auxiliary Co-product Addition):

In the second scenario, we evaluate the investment decision of integrating the FS and NS units with the base system. The FS and NS units bring their own associated costs and revenues, which contribute to the total costs and revenues of the base system. We initially introduce the FS unit to the base system and calculate the NPV, considering the possibility of selling the auxiliary co-product as either a peat moss replacement (high-value fiber) or a soil amendment (low-value fiber). Subsequently, we add the NS unit to the previous configuration and calculate the NPV of the fully integrated system.

Scenario 3 (Environmental Credits):

The third scenario explores the potential impact of securing environmental credits on the economic viability of the base AD system. Our analysis considers the existing environmental credits available in New Mexico and explores the theoretical possibility of introducing additional credits currently unavailable in the state. The types of credits available for the CNG and CHP systems are different, with their own revenue parameters affecting the viability of a system.

Unlike Scenario 2, obtaining environmental credits does not require the installation of additional technological components and therefore does not incur additional capital and O&M costs. However, some environmental credits may have associated transaction costs, such as a percentage of the credit claim or a fixed price. The parametric values of environmental credits are available in Table 4.4 and Table 4.5.

Scenario 4 (Co-product Addition plus Environmental Credits):

Finally, in the fourth scenario, we evaluate the viability of an integrated AD system by considering both auxiliary co-product sale and environmental credit acquisition possibilities. This scenario represents the combination of the most realistic and conservative aspects of Scenario 2 and Scenario 3. For instance, we assume that all the fiber produced by the FS unit is sold as low-value fiber and only those credits that are currently available in New Mexico are considered for environmental credit acquisition. This comprehensive assessment enables a deeper understanding of the factors influencing the profitability of AD systems with either CHP or CNG technologies.

3.4 Calculation of External Social Benefits

Quantifying GHG Emission Savings

The potential savings in GHG emissions, contingent on methane combustion from the AD systems (CHP or CNG), is outlined in this section. A comprehensive GHG budget, inclusive of lifecycle assessment of dairy farms and the associated supply chain such as feed production and various phases of dairy cow development, lies beyond the scope of this study. Consequently, emissions linked to the transportation of manure or feedstock and additional emissions within production processes are not incorporated in our calculations. We estimate the GHG emission savings by contrasting methane emissions from dairy cows with the amount of methane theoretically capturable and convertible to carbon dioxide via anaerobic digestion. The calculation is carried out as follows:

$$G = \left(\frac{\kappa x e S}{1000}\right) \tag{7}$$

where,

$\kappa = 76.65 \frac{kg}{cow} / year$ represents the annual per cow methane emission from manure (Todd et al., 2011), $e = 28\ tons\ CO2e$ denotes the GHG savings achieved by combusting a ton of methane to carbon dioxide, as specified by the Intergovernmental Panel on Climate Change (2014). The monetary value assigned to each ton of carbon dioxide equivalent saved is denoted by S, which is an estimate of the social cost of carbon, encapsulating the economic damage from GHG emissions. Current EPA guidelines and recent research suggest this value to fall between \$51 and \$190 (IWG, 2021; Rennert et al., 2022).

Quantifying Health Benefits from Air Pollution Abatement

AD systems can also yield health benefits, given their role in curtailing primary and secondary pollutants. Studies have suggested that AD systems integrating nutrient separation generate most of these benefits. In fact, the application of digested manure into the field without nutrient separation may even increase the ammonia emissions over a short duration. Therefore, the inclusion of a nutrient separation module in the AD system contributes to a higher external health benefit, while a system devoid of nutrient separation could potentially yield negative external health benefits.

Ghimire et al., (2023) determined that the monetary value of reduced mortality due to reduction in ammonia emissions can range from $468 to $1634 per cow, dependent on the location of the dairy farm in New Mexico. Certain studies have shown nutrient recovery of ammonia from the fiber to range from 57% to 86% (Shi et al., 2022). We have adopted the lower value of this recovery factor (57%), estimating our health benefits from reduced ammonia emissions to range from $267 to $931.

3.5 Risk Assessment

Sensitivity Analysis

Sensitivity analysis is a critical aspect of any quantitative study, serving as a litmus test for the robustness of the results against the volatility of the input parameters. In this study, we assess the impact of variations in both prices and functional parameters on the NPV of two AD systems—CHP and CNG—in the context of a typical farm in New Mexico with 3,187 cows.

Our sensitivity analysis considers all potential and existing revenue streams, even those currently unattainable, to provide a comprehensive evaluation of each parameter's impact on the NPV. The sensitivity analysis was performed using two different sets of input parameters. In the first set, the parameters were directly related to the revenue streams, including the prices of electricity, carbon credits, RECs, tax credits, fiber, phosphate, and sulfate. In the second set, the parameters were related to the capital investment and the calculation of NPV, including the discount rate, capital lifetime, and capital cost.

The price parameters were changed between zero to two times their original values to illustrate the effect of a missing revenue stream and the potential impact on NPV if the price was doubled.

On the other hand, functional parameters were adjusted between 0.5 to 1.5 times their original values to explore the impact of halving or a 50% increase in parameters on the NPV.

For each variation of parameters, we computed the NPV and stored the results in a data frame. The data frame was then used to create a plot, showing the variation in NPV as a function of the parameter variation. Each parameter is represented by a different color, allowing for an easy comparison of their relative impacts on the NPV.

The sensitivity analysis identifies the parameters that most significantly affect the NPV. It should be noted that, while our NPV is conjectural due to its hypothetical assumptions, it serves as a valuable indicator when assessing the differences in NPVs arising from parameter changes.

Monte Carlo Analysis

A triad of Monte Carlo simulations were performed to examine how stochasticity in price parameters affects the NPV of an AD system. This assessment explicitly explored three scenarios associated with the uncertainty in carbon credit pricing, focusing on its impact on the NPV of a typical New Mexican dairy farm with 3,187 cows. The Monte Carlo simulation was applied to the optimal configuration of the AD system (AD+CHP+FS+NS), as established by deterministic evaluations. The three distinct calculations are as follows:

i) Stochasticity in prices of all co-products and existing environmental credits, including the attainment of RECs and carbon credits.

ii) Stochasticity in the prices of co-products and carbon credits, excluding the attainment of RECs.

iii) Stochasticity restricted to the carbon credit prices, while the coproduct prices remain constant, excluding the attainment of RECs.

Each price parameter adhered to a triangular distribution, informed by both prevailing and assumed price data. A triangular distribution is a continuous probability distribution with a probability density function shaped like a triangle. It is defined by three values: the minimum value, the maximum value, and the mode. In this case, these values represent the range and most likely values of each price parameter.

This Monte Carlo Analysis facilitates an in-depth exploration of the potential variability in the NPV due to the stochastic nature of price parameters, thereby providing a more robust and realistic understanding of the economic viability of the AD system.

4. Data

This study draws on multiple data sources to assess the viability of different configurations of AD systems. An AD system can have different technological components, each with their own costs and revenues. The cost and revenue functions used in this study were obtained from Astill and Shumway (2016) and were based on the Anaerobic Digester System Enterprise Budget Calculator. These parameters originally developed by AD engineers, were collected from previous studies and industry partners. To adjust for inflation, the dollar value associated with the capital infrastructures was updated to 2021 dollars using Chemical Engineering Price of Construction Indices (CEPCI) (Access Intelligence, 2023). The operation and maintenance costs were also updated to 2021 prices using the Consumer Price Index (CPI). When official sources were available, the price of co-products and environmental credits were updated to 2021 levels.

In their absence, they were adjusted using the CPI. All values reported in the study were annual unless otherwise stated.

4.1 Costs and Revenues

Both capital and operating costs are important when assessing the viability of an AD system. Capital costs, a one-time expenditure, are incurred at the project's inception, encapsulating the cost of infrastructure, machinery, installation labor, and other startup expenses. Conversely, operating and maintenance (O&M) costs are recurring costs over time which are assumed to be steady in our analysis. The parametric values of capital costs and O&M costs are listed in Tables 1 and 2 as follows.

Table 1: Cost parameter for capital cost (adjusted to 2021 dollars using CEPCI and CPI)

	v_1	f_1	v_2	f_2	α
AD	158	2,263,545	786	694,556	2500
CHP	322	828,790	-	-	-
CNG	593	1,530,182	-	-	-
Fiber Separation	50	-	-	-	-
Nutrient Separation	508	24,112	-	-	-

For the AD unit, its capital cost function varies depending on the threshold size of the system represented by α. For systems that have fewer than 2500 cows, v_1 and f_1 are used for the calculation of capital cost whereas for systems than have 2500 or more cows, the cost function with v_2 and f_2 are used. This variation reflects the different cost dynamics associated with different sizes of AD systems.

Table 2: Cost parameter for O&M cost (adjusted to 2021 dollars using CEPCI and CPI)

	w_1	g_1	w_2	g_2	β
AD	36	-	-	-	-
CHP	81	2,521	67	62,679	4500
CNG	32	43,812	-	-	-
Fiber Separation	7	-	-	-	-
Nutrient Separation	115	-	-	-	-

For the CHP unit, the threshold size of the farm related to O&M costs as represented by β is 4500. For CHP systems that have lower than 4500 cows, w_1 and g_1 are used as variable and fixed costs respectively. However, when the size of farm increases to 4500 or more cows, w_2 and g_2 are used for the calculation of O&M costs.

The revenue generated by an AD system hinges on several determinants. Our assessment only considers the cash flows related to the investment, defining the system boundary by excluding all costs and revenues that would have transpired irrespective of the AD system's adoption. Thus, activities such as milk production and on-farm crop production, although inextricably linked with the AD system, are excluded from our assessment. Our focus remains affixed on benefits that farmers can materialize as revenue streams. For instance, cost savings resulting from heat generation do not enter our calculation, as we only consider co-products with a potential market. Revenues can be generated through two channels: firstly, by selling co-products, and secondly, by availing various environmental credits. The revenue parameters for all technology components associated with the sales of coproducts are outlined in Table 3.

Table 3: Revenue parameters (adjusted to 2021 dollars using CEPCI and CPI)

	z_1	p_1	z_2	p_2
CHP	1,703	0.06	-	-
CNG	21	6.03	-	-
Fiber Separation	1	165.34	1	25.6
Nutrient Separation	0.92	103.24	0.4	372

The complexity of our system necessitates a more nuanced representation for certain technological components. For instance, nutrient separation unit concurrently yields multiple auxiliary co-products (sulfates and phosphates). The fiber separation unit on the other hand yields a single auxiliary co-product that can be marketed under different labels and price points depending on the market conditions. To accommodate this intricacy, we introduce z_2 and p_2 into our calculation. Here, z_2 denotes the marginal output of the second co-product or alternatively it represents the marginal output of the same product when sold at a different price point. In the same vein, p_2 represents the price of the second co-product or the price of the same product sold under a different label.

The acquisition of environmental credits generates revenue for the farmers. which can be claimed after the sales or at the end of year in the form of tax rebate. This revenue, which can be realized immediately upon the sale of credits or at the end of the year as a tax rebate, plays a significant role in our analysis. We assume that the revenue is acquired directly after the sale, similar to the transaction process for any coproduct sales.

The process of acquiring environmental credits does not necessitate the installation of new machinery nor does it impose additional operations and maintenance costs. However, certain transactional costs may be incurred. These costs can be a fixed percentage of the revenue or a combination of lumpsum amount and a percentage cut from the revenue. Table 4 and Table 5 list the parameters associated with revenue generation and transactional costs of environmental credits.

Table 4: Revenue parameter for environmental credits (adjusted to 2021 dollars using CEPCI and CPI)

	a_1	p_2
Carbon credit	3	22.04
REC	1,703	0.20

Tax credit	1,703	0.02
RIN	247	1.58
LCFS	6	187.11

Table 5: Transaction costs of environmental credits (adjusted to 2021 dollars using CEPCI and CPI)

	a_2	p_2	b
Carbon credit	0.35	22.04	5,250
REC	17	0.20	-
RIN	25	1.58	-
LCFS	0.6	187.11	-

4.2 Variables and Parameters

Table A1 in the appendix lists all the variables and parameters used in this study. NPV is calculated employing a 4% real discount rate and a 20-year capital lifetime, consistent with Astill and Shumway (2016) and other pertinent literature. The value of x represents the total number of milk cows in a dairy farm and thus reflects the farm's size. We assume that 42.75 cubic meters of manure is produced per WCE per year, of which 90% is collected and deployed in the AD system.

The prices of electricity and CNG used in our study are based on the average 2021 prices of the Southwest region. The CNG scrubbing rate, which signifies the percentage of biogas transmuted to CNG is derived from Astill and Shumway (2016). The fiber separation system produces high-value fiber, which can potentially be traded as a peat moss replacement for $165.34 per ton or as a soil amendment for $25.6 per ton, adjusted to 2021 dollars. The price of ammonium sulfate hinges on the June 2021 market price, which has experienced a significant increase in recent years. The price of phosphate is predicated on Astill and Shumway (2016), adjusted to 2021 dollars.

The price of environmental credits is obtained from official sources. Carbon credit prices are based on the 2021 average auction settlement price in the California cap and trade market. Renewable energy certificate (REC) prices are predicated on industry data for Xcel Energy, which delivers electricity and natural gas to parts of Eastern New Mexico overlapping with dairy-producing regions. Renewable Identification Number (RIN) prices are based on the average price of qualified RIN in 2021 as published by the US EPA.

New Mexico has a renewable energy production tax credit in place. However, its tax structure is complicated and subject to statewide limits, introducing uncertainties regarding eligibility and claimable amounts. Therefore, we use a simplified tax incentive structure, as per Astill and Shumway (2016), to discern how it might invigorate the growth of AD systems in the state. Concurrently, despite the non-existence of a Low Carbon Fuel Standard (LCFS) in New Mexico at present, ongoing legislative discourse suggests its imminent implementation. Therefore, we incorporated it as a prospective credit scheme for New Mexico, based on the 2021 average LCFS prices in California.

5. Results

5.1 Deterministic Scenario Analysis

Scenario 1 (Baseline):

Figure 2 delineates the NPVs of a continuous range of herd sizes up to 25,000 cows, employing either CHP or CNG technologies, while solely selling the primary products of electricity or CNG, respectively. The results demonstrate a persistent negative NPV across all dairy farm sizes, indicating that in the absence of auxiliary co-product sales or environmental credits, the base AD system does not generate positive revenue. Moreover, an inverse relationship between farm size and NPV is observed, with larger farms registering greater negative NPV values. This pattern persists for both CHP and CNG systems.

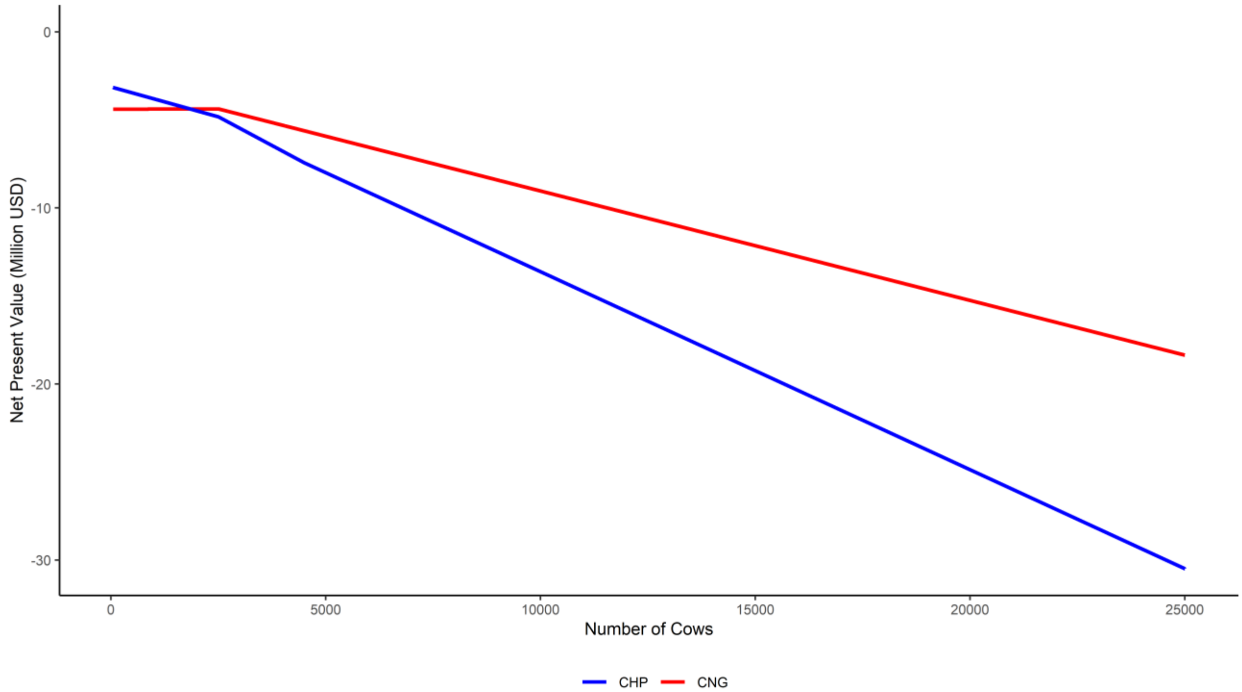


Figure 2: NPV of CHP or CNG systems, by herd size

Scenario 2 (Auxiliary Co-product Addition):

Figure 3 presents the NPVs of a continuous range of herd sizes up to 25,000 cows, utilizing either CHP or CNG technologies, while also incorporating auxiliary co-products derived from auxiliary components. Specifically, our assessment focuses on the integration of a fiber separation unit and a nutrient separation unit, with the co-products of interest being fiber and nutrients. As mentioned earlier, the fiber can be sold as a peat moss replacement or soil amendment, contingent upon prevailing market conditions.

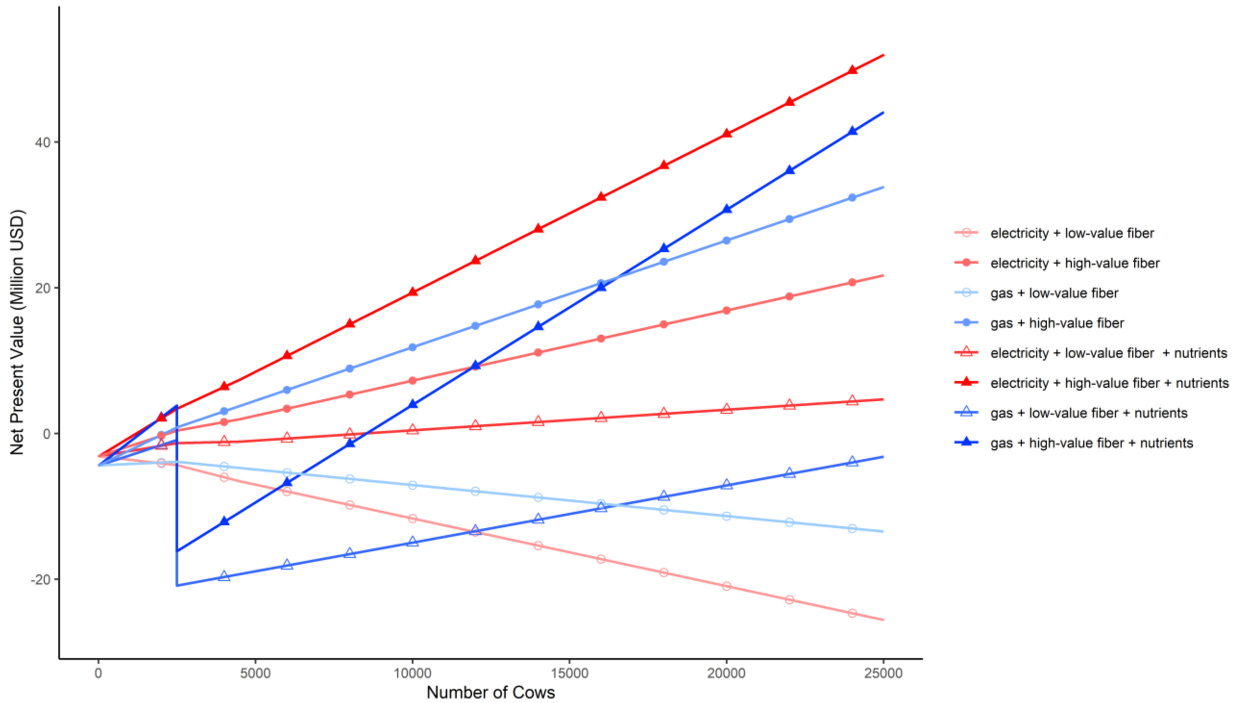


Figure 3: NPV of CHP or CNG systems with auxiliary co-products, by herd size

For the configuration where fiber is sold as a low-value soil amendment, both CHP and CNG systems exhibit negative NPVs across all farm sizes. Conversely, when fiber is sold as a high-value peat moss replacement, both technologies generate positive NPVs beyond a certain farm size. The breakeven size for farms adopting CHP+FS and selling the fiber as peat moss replacement is 2,220, while the breakeven size for farms adopting CNG+FS and selling the fiber as peat moss replacement is 2,097.

Additionally, the integration of a nutrient separation unit into the systems comprising fiber separation results in elevated NPVs. For a system deploying CHP+FS+NS and selling the fiber as a low-value soil amendment, the breakeven size is 8,479. In contrast, while the NPV of a system deploying CNG+FS+NS increases with herd size, it does not reach a positive value within the range of our study. Therefore, no breakeven size can be identified for this specific technology configuration.

Finally, when the systems—both CHP+FS+NS and CNG+FS+NS—are capable of selling the fiber as a high-value peat moss replacement, their NPVs markedly increase, achieving breakeven sizes at 1,203 and 1,336, respectively.

Scenario 3 (Environmental Credits):

Figure 4 depicts the NPVs of a continuous range of herd sizes up to 25,000 cows, utilizing either CHP or CNG technologies, while also capitalizing on environmental credits. We evaluated two scenarios: one with existing environmental credits and another with all potential credits. CHP and CNG systems can claim distinct environmental credits. Currently, CHP systems can claim carbon credits and RECs, while CNG systems can claim RINs. By claiming these credits, the NPV of the system swiftly escalates, resulting in a breakeven size of 665 for CHP systems and 918 for CNG systems. Although not currently available, CHP systems can also theoretically claim tax credits, which curtails the breakeven size to 606. Similarly, CNG systems can theoretically claim LCFS credits, which notably improves the system's profitability and lowers the breakeven size to 229. When only existing environmental credits are considered, the CHP system yields a higher NPV compared to the CNG system, whereas the CNG system exhibits a significantly higher NPV when all theoretically possible credits are taken into account.

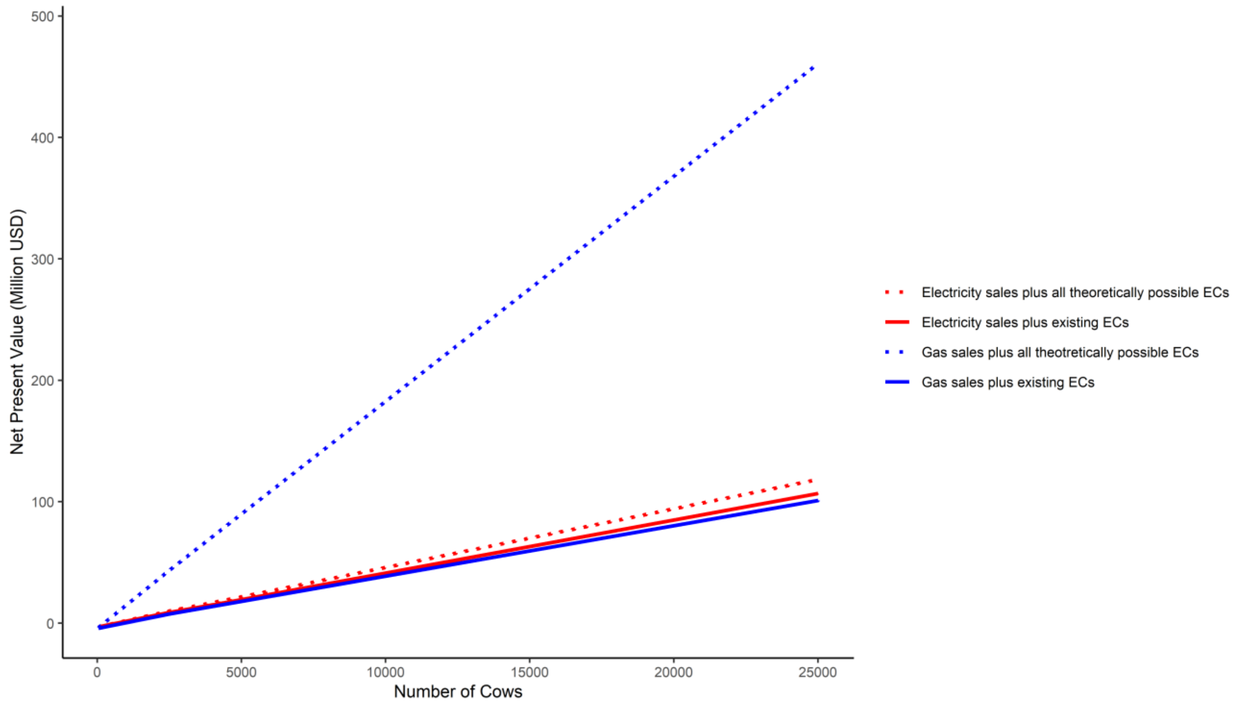


Figure 4: NPV of CHP or CNG systems with environmental credit acquisition, by herd size

Scenario 4 (Co-product Addition plus Environmental Credits):

Figure 5 presents the NPVs of a continuous range of herd sizes up to 25,000 cows, deploying either CHP or CNG technologies, and incorporating co-product sales along with existing environmental credit realization. In this assessment, we operate under the conservative assumption of selling fiber as a low-value soil amendment. Initially, we examine the integration of fiber separation components and existing environmental credits into the AD systems, followed by the addition of nutrient separation components to the previous configuration, and compute the corresponding NPVs. For systems incorporating fiber sales and existing environmental credits, the breakeven size for CHP and CNG systems are 620 and 856, respectively. With the incorporation of both fiber and nutrient sales along with the attainment of existing environmental credits, the breakeven size for CHP and CNG systems decreases to 379 and 522, respectively. Our results indicate that the CHP system exhibits a higher NPV in both configurations.

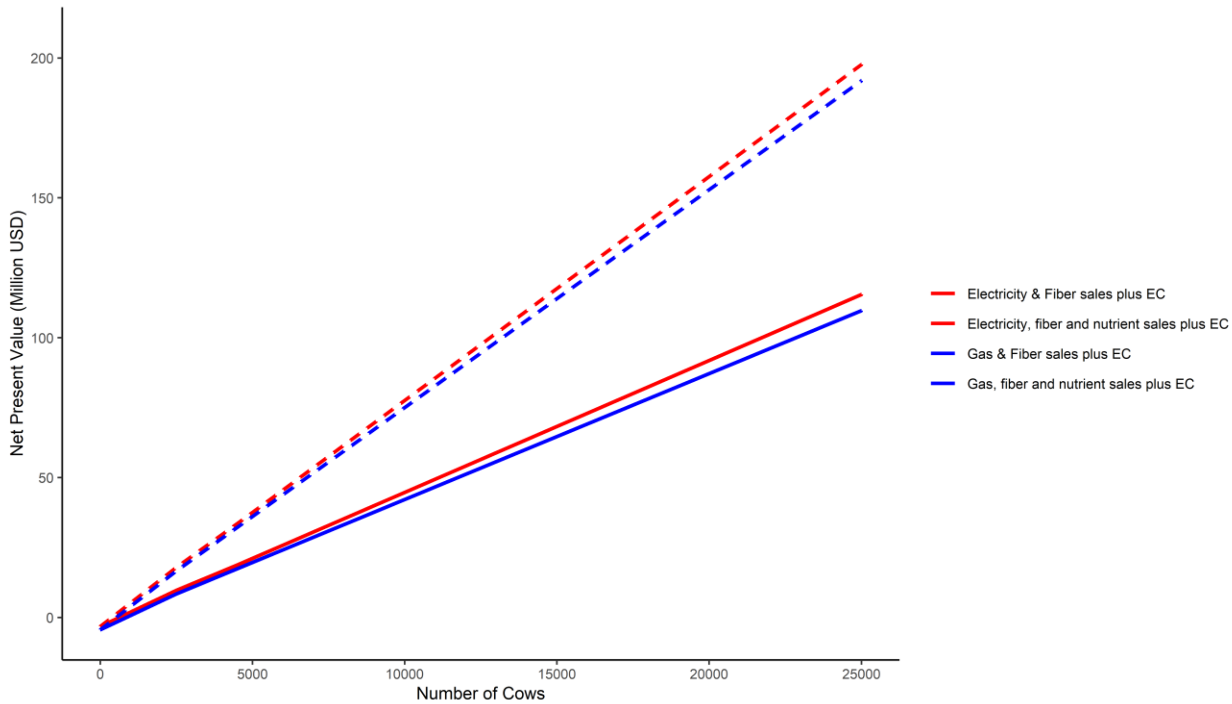
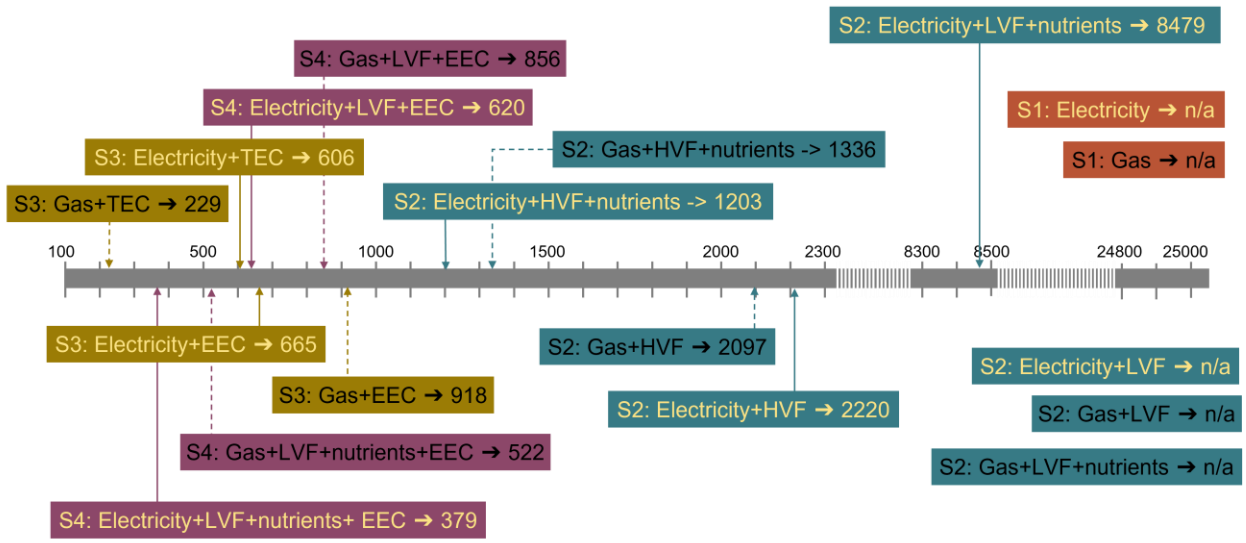


Figure 5: NPV of CHP or CNG systems with Co-product sales and environmental credits obtention, by herd size.

Assessment of Breakeven Sizes

Figure 6 provides the breakeven sizes of AD systems across an array of scenarios and configurations. AD systems that rely solely on the sale of gas or electricity do not yield a positive NPV for any farm size, thereby precluding the possibility of a breakeven size, as evidenced in Scenario 1.



* Note: LVF = Low-value fiber, HVF = High-value fiber, EEC = Existing environmental credits, TEC = Theoretically possible environmental credits

Figure 6: Breakeven size for each scenario and configurations

A similar pattern emerges in Scenario 2, where AD systems centered on selling electricity combined with low-value fiber or gas, or gas coupled with low-value fiber, likewise fail to generate a positive NPV, thus ruling out breakeven sizes. However, the table changes with the addition of high-value fiber to the equation. The breakeven size for systems leveraging electricity and high-value fiber is noted to be 2,220, while those utilizing gas and high-value fiber exhibit a slightly lower breakeven size of 2,097.

When nutrients are incorporated into the mix, we observe that the breakeven size for configuration producing electricity paired with low-value fiber and nutrients is 8,479. In contrast, gas systems featuring low-value fiber and nutrients do not reach a breakeven size due to their inability to generate a positive NPV at any farm size. The breakeven sizes for electricity and gas systems that integrate high-value fiber and nutrients drop to 1,203 and 1,336, respectively.

In Scenario 3, where environmental credits are claimed, AD systems experience a boost in profitability, which in turn diminishes the breakeven size. Systems that combine electricity and existing environmental credits reach a breakeven size of 665, while the configuration with gas attain a breakeven size of 918. If all theoretically possible credits are incorporated, the breakeven sizes further contract to 606 for electricity and 229 for gas.

Scenario 4, which amalgamates the more realistic aspects of Scenarios 2 and 3, witnesses further enhancements in profitability. For instance, the breakeven size for electricity combined with low-value fiber and existing credits is 620, compared to 856 for gas paired with low-value fiber, nutrients and existing credits is 379, while the same configuration for CNG systems registers a slightly higher breakeven size of 522.

5.2 Calculation of External Social Benefits

Quantifying GHG Emission Savings

Based on the range of social cost of carbon values of $51 to $190, the monetary value of annual GHG savings per cow would range from $109 to $408. If we consider a hypothetical scenario where all the farms in New Mexico with a total of 292,000 cows adopt AD systems, then the total GHG savings would amount to be $32 million to $119 million per year. For an average dairy farm in New Mexico with 3,187 cows, the GHG savings would range from $0.35 million to $1.3 million per year.

Quantifying Health Benefits from Air Pollution Abatement

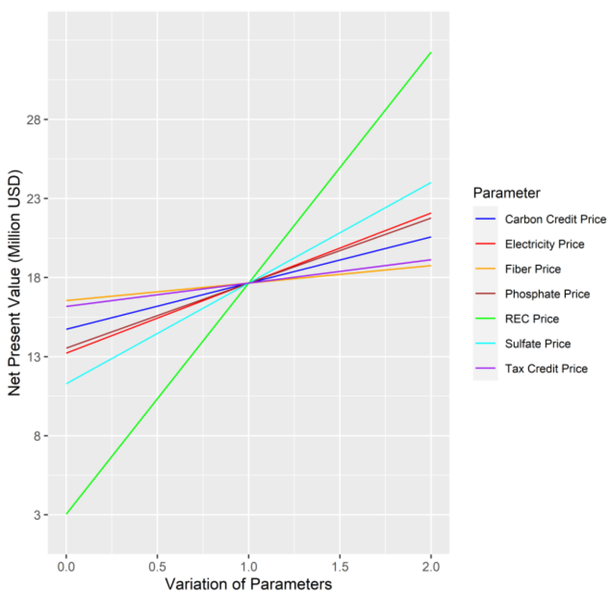
Using a range of marginal benefits of ammonia reduction from $267 to $931 for an AD system equipped with nutrient separation, we calculated the associated health benefits. If the entire state of New Mexico adopted AD systems with nutrient separation, the total health benefits would be between $78 million and $272 million. For an average dairy farm in New Mexico with 3,187 cows, the annual health benefits resulting from ammonia abatement would range from $0.86 million to $2.97 million per year depending on the location of the farm.

5.3 Risk Assessment

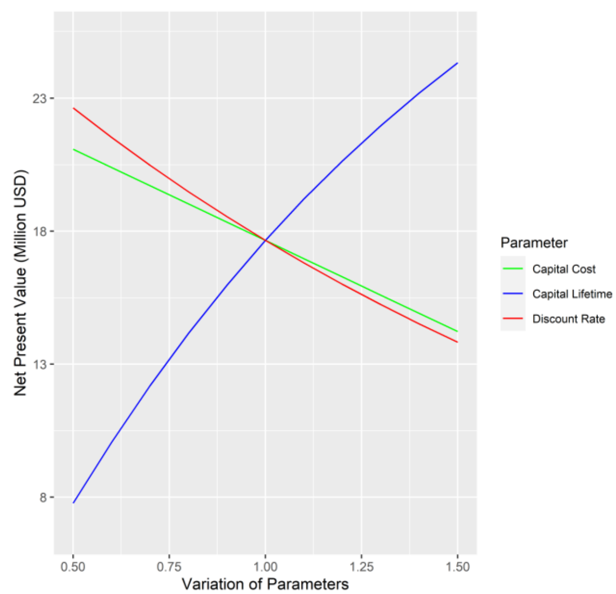
Sensitivity Analysis

A sensitivity analysis was conducted to delve into the fluctuating influences of different price parameters on the economic feasibility of two systems—CHP and CNG—within an AD framework. Figure 7 presents the results of this analysis, depicting the sensitivity of the NPV to varying prices and functional parameters.

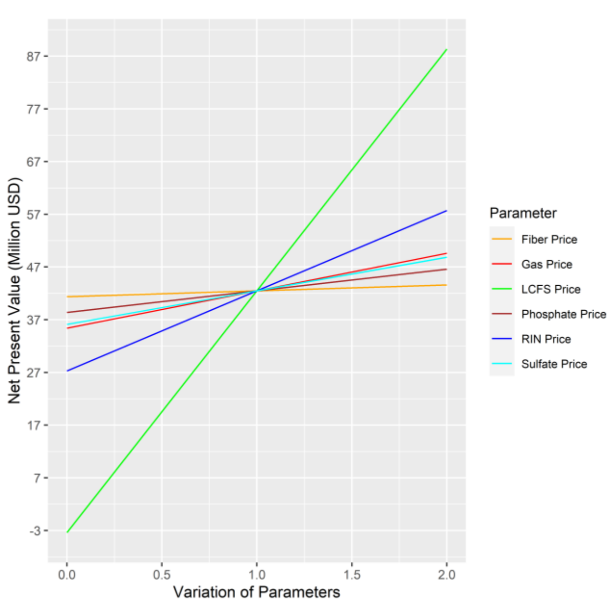
A) Varying prices (CHP system)



B) Varying functional parameters (CHP system)



C) Varying prices (CNG system)



D) Varying functional parameters (CNG system)

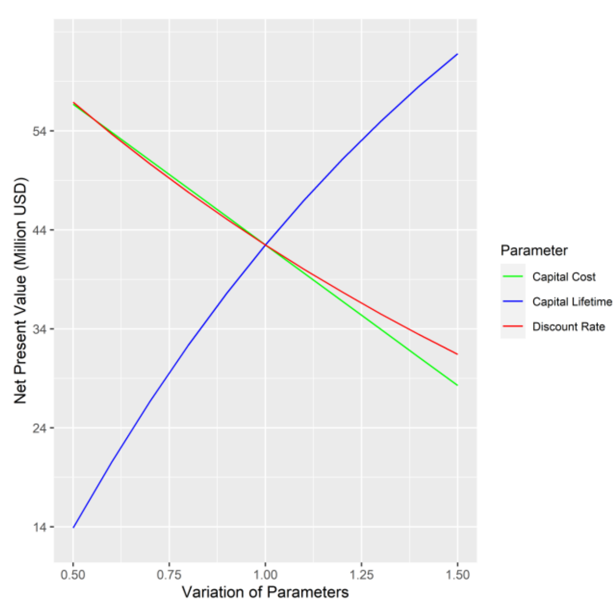


Figure 7: Sensitivity analysis of the CNG and CHP system for a farm size of 10,000 cows varying price levels and functional parameters.

In the CHP system, the REC price was found to be the most sensitive parameter. This sensitivity can be observed starkly when the REC price is reduced to zero, simulating a scenario where REC is no longer available. This results in a substantial drop in the Net Present Value (NPV) of the system from approximately $18 million to a mere $3 million. Other sensitive parameters in descending order of influence include the prices of sulfate fertilizer, electricity, and phosphate fertilizer. The least sensitive parameters were found to be fiber price, tax credit and carbon credit prices, implying the relative insensitivity of NPV to changes in these variables.

For the CNG system, the LCFS price is the most sensitive parameter. This is evident when the LCFS is removed, causing the NPV of the system to plummet into negative territory, from around $42 million to negative $3 million. The RIN price, gas price, and sulfate fertilizer price follow suit in terms of sensitivity. The least sensitive parameters for this system are the fiber price and the price of phosphate fertilizer, suggesting that changes in these parameters will have a lesser impact on the system's NPV.

The sensitivity analysis also extended to functional parameters, revealing a high level of sensitivity to all three parameters - discount rate, capital cost, and capital lifetime - for both the CHP and CNG systems. The NPV exhibits an inverse relationship with the discount rate and capital cost, while it shows a positive relationship with the capital lifetime. A reduction in capital lifetime by half to 10 years precipitates a decline in the NPV of the CHP system to around $8 million from $18 million, and for the CNG system, it drops to $14 million from $42 million. As the opportunity cost of the investment increases, as denoted by the rise in the discount rate, the NPV of the system diminishes sharply for both systems. Furthermore, the NPV of both the CHP and CNG systems is highly susceptible to shifts in the capital cost. A halving of the capital cost significantly bolsters the profitability of both systems, as is clearly illustrated in the accompanying graphs.

Monte Carlo Analysis

A triad of Monte Carlo Analyses were performed to examine the influence of volatility in price parameters on the NPV of the most optimal configuration of the AD system. The deterministic assessment identified CHP+FS+NS with environmental credit acquisition as the most optimal configuration. In this context, we explored three scenarios focusing on the uncertainty in carbon credit prices to determine their impact on the NPV of a typical dairy farm in New Mexico that has adopted the optimal AD configuration with a herd of 3,187 cows.

First, we introduced uncertainties across all price parameters. The PDF graph in Figure 8 shows that most NPV values are densely concentrated between $5 and $10 million. The CDF graph demonstrates that the likelihood of zero NPV is virtually negligible. Therefore, for an average dairy farm generating revenues from electricity, fiber and nutrient sales, in addition to carbon credits and RECs, the economic rationale supports investing in the AD system. This is due to the practically non-existent probability of incurring a loss within the acceptable risk boundaries of price fluctuations.

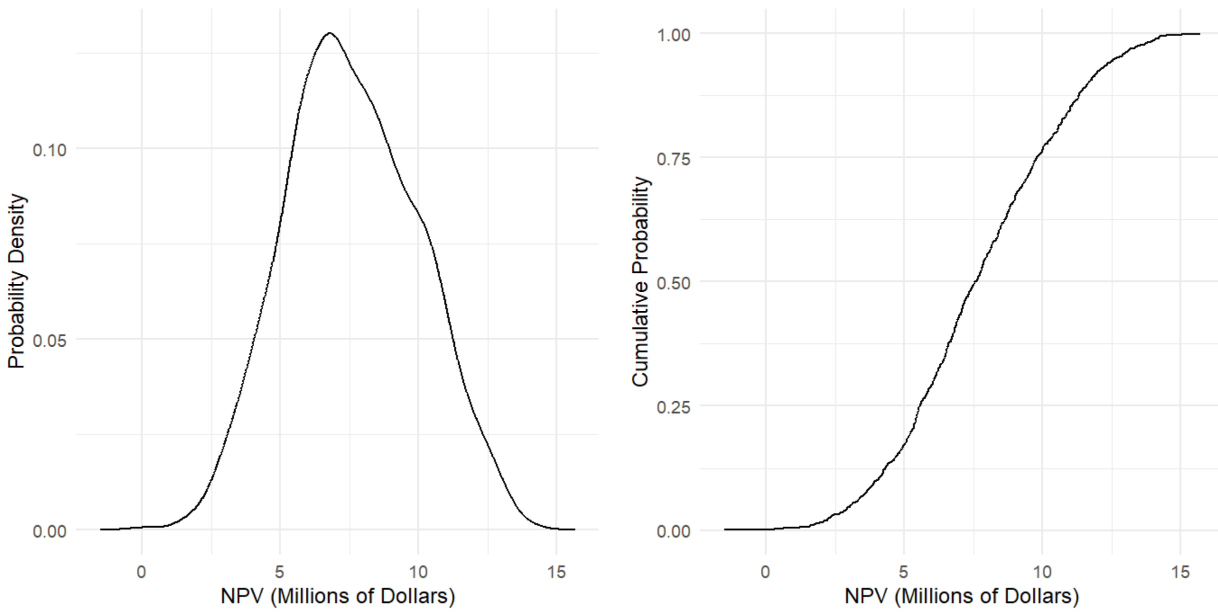


Figure 8: Probability distribution function (PDF) graph and cumulative distribution function (CDF) graph of a typical dairy farm adopting CHP+FS+NS with stochastic prices of all co-products and existing environmental credits (carbon credits + RECs)

Next, we considered a scenario where a typical New Mexican dairy farm can procure carbon credits but not the RECs. All price parameters maintain the same level of uncertainty as before. The PDF graph in Figure 9 indicates that most of the NPV values are concentrated between -$2 and $2 million. Given the absence of REC and the uncertainties pertaining to the prices of co-products and carbon credits, the viability of an AD project becomes questionable. This conclusion is further validated by the CDF graph, which indicates that the viability of the AD project resembles a coin-flip decision, balanced precariously with a 50% chance of failure and a 50% chance of success.

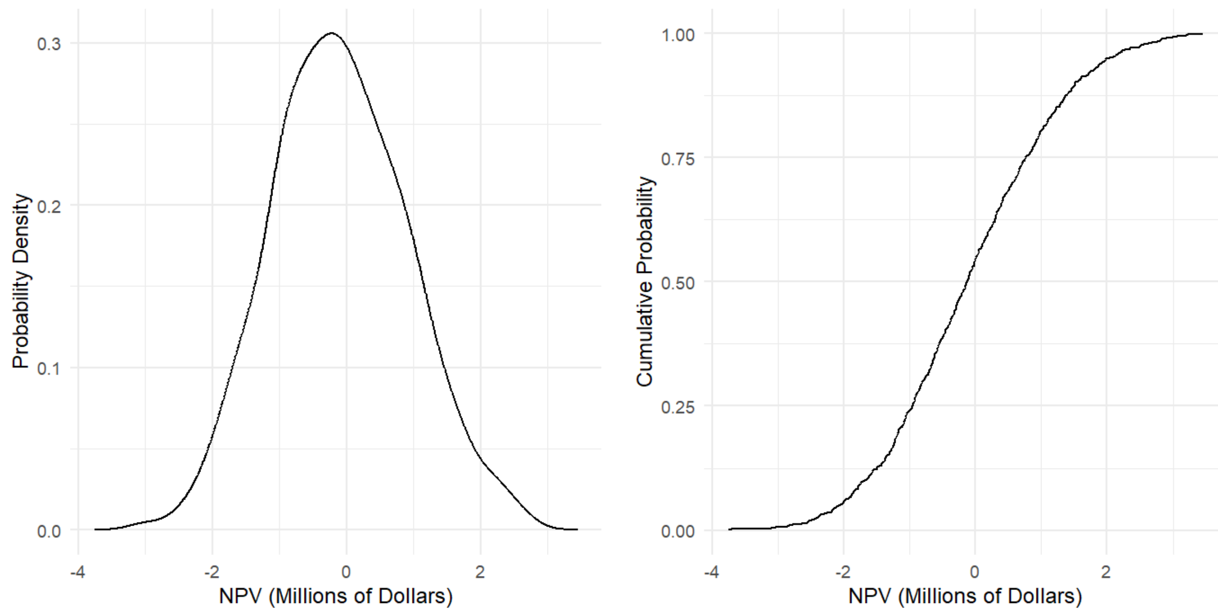


Figure 9: The PDF graph and the CDF graph of a typical dairy farm adopting CHP+FS+NS with stochastic prices of co-products and carbon credits

For the last scenario we consider stochasticity in carbon credit prices and stable prices of co-products sold. We exclude the possibility of attaining RECs in this scenario as well. The PDF graph in Figure 10 illustrates that although the NPV of the AD system remains predominantly positive, it is not as significant as in the first scenario. The CDF graph corroborates this observation. The outcome indicates that carbon credits can still serve as an enticing incentive for AD operators to remain viable, particularly in the absence of other more lucrative incentives, assuming that the prices of other co-products remain stable and relatively high within the market range. The tail on the left of the graph representing the worst possible outcomes suggests that there is a non-zero chance of negative NPV, and the AD operators should be aware of and be prepared for this low probability but potentially high impact event.

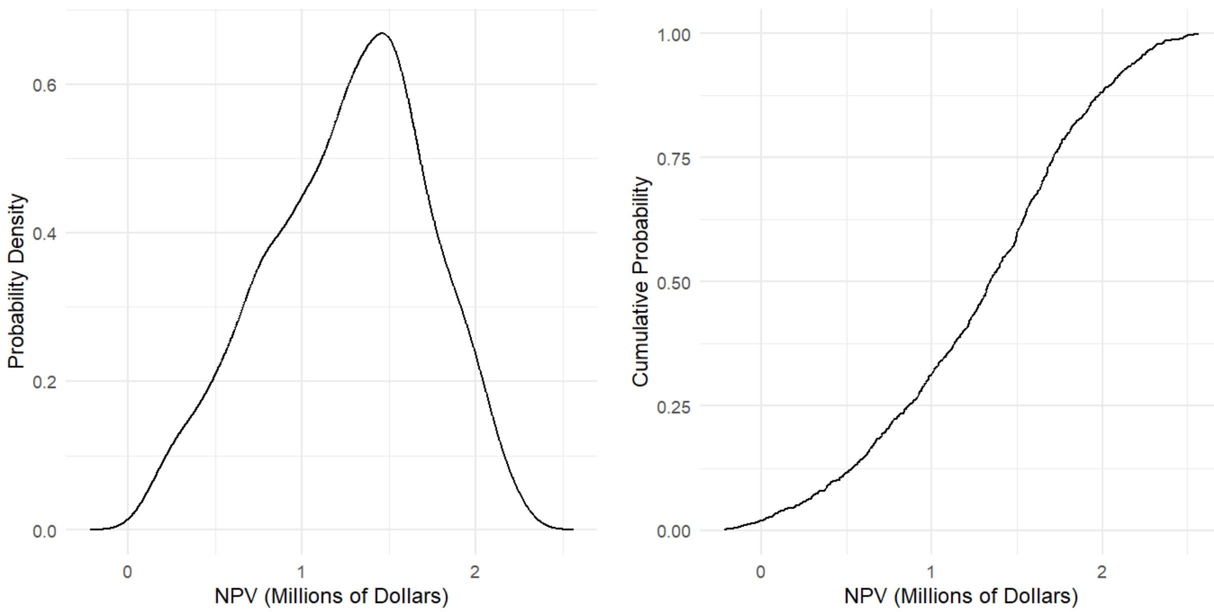


Figure 10: The PDF graph and the CDF graph of a typical dairy farm adopting CHP+FS+NS with stochastic carbon credit prices and stable co-product prices

6. Conclusion and Discussion

We conducted a comprehensive assessment to evaluate the potential and viability of AD system installation in dairy farms across New Mexico. The analysis involved four distinct scenarios and utilized NPV as a measure of investment viability. The scenario analysis was conducted under deterministic conditions to provide an overview of viability for all revenue streams and farm sizes. Additionally, we performed a stochastic assessment of NPV to offer a more realistic account of the outcomes for a typical dairy farm in New Mexico. Furthermore, we calculated the social benefits associated with AD systems, specifically focusing on methane destruction, GHG emission savings, and nutrient separation to mitigate health risks and particulate matter formation, resulting in human health benefits. Lastly, we conducted a sensitivity analysis to demonstrate the impact of changing various parameters on the results.

Our analysis identified the CHP system with fiber and nutrient separation as the most optimal configuration in terms of both financial and environmental benefits. A marginal analysis of costs and revenues for this ideal configuration is necessary to gain a deeper understanding of the financial aspects. For an average New Mexican dairy farm with 3,187 cows, the marginal NPV of the optimal configuration is $5,077 per cow. The configuration has a marginal capital cost of $2,150 per cow and a marginal O&M cost of $3,267 per cow. With a marginal revenue of $10,495 per cows, the system's gross margin is about 48%. The revenue and costs calculated here are based on the present value of cashflows generated in the project's lifespan of 20 years. When we break down the revenue to highlight the contribution from different components of the system, we can see that revenue from RECs contributes the most (43.68%), followed by nutrient separation (31.31%). Electricity sales, the main product of the CHP system, account for only 13.23% of the overall revenue. Carbon credit and fiber sales contribute the least with 8.48% and 3.30% respectively. While this analysis reveals that certain revenue sources contribute less than others, sustaining all revenue streams is critical to ensuring the portfolio diversification and dispersal of the risk associated with the discontinuance of a revenue source.

If we consider the external benefits of AD systems, the question of whether to install such a system becomes less relevant, the question rather turns into when and where to install it. The marginal external benefits of AD systems are substantial: the benefits from GHG emission savings over 20 years range from $1,789 to $6,697 per cow, depending on the social cost of carbon used. We assume a 4% discount rate and 2% annual appreciation in the value of social cost of carbon in this calculation. Additionally, the marginal health benefits from reduced pollution range from $4,382 to $15,281 per cow, depending on the location of the AD system. The marginal external benefits range from $6,171 to $21,978 per cow, whereas the marginal private benefits amount to $10,495. This indicates that the positive externality of AD systems may not be fully captured by the realization of private benefits alone. In some cases, government intervention and incentives may be necessary to internalize this externality and achieve an optimal level of AD installation.

The livestock sector has faced criticism for its contribution to climate change, leading to a negative perception among consumers. To meet changing consumer demands and improve their environmental image, livestock operations can adopt AD systems, actively reducing their carbon and pollution footprints. This aligns with the growing trend seen in other industries, such as the airline sector where companies actively emphasize and publicize their emissions reduction initiatives. By embracing AD systems, the livestock sector can address environmental concerns, rebrand themselves as climate-friendly, and potentially command higher prices. This strategic shift in perception sets them apart from competitors not prioritizing environmental stewardship, enhancing their reputation and profitability. Embracing sustainable practices allows the livestock sector to thrive in a consumer landscape valuing climate-conscious product.

The sensitivity analysis highlights the reliance of AD systems on environmental credits for their viability. However, it is important to acknowledge that these credits can be conditional, subject to quotas or terms, and may even be discontinued due to regime changes or other factors. Additionally, some farmers hold principles that oppose receiving government handouts, including these credits (Cowley & Brorsen, 2018). Capital cost has also been consistently identified as a critical factor affecting NPV installation. Our sensitivity analysis supports the argument that reducing the cost of capital may generate positive NPVs for otherwise unprofitable operations. To address this challenge, providing grants to offset the initial costs of AD implementation could be instrumental in persuading hesitant farmers to embrace the technology. Likewise, offering low-interest loans presents another avenue for individuals who hold principles opposing government assistance. These initiatives can support the implementation of AD systems and help overcome financial barriers, contributing to their long-term viability.

There are some caveats to our study that warrant discussion. When calculating NPVs, we assumed an idealistic world where every legal and administrative hurdle is overcome, and every component functions smoothly. However, the real world is rarely so perfect. Although our stochastic assessment incorporated uncertainties across prices, the real world could present even greater challenges, such as a lack of market for the products produced by the AD system. Production does not always equal sales; however, we assumed them to be equivalent. We might not be able to connect electricity to the grids, or there might be too many technical and administrative hurdles. The fiber produced might not find a market due to the lack of agricultural land nearby, the high cost of hauling farther distances, or the unwillingness of farmers to accept manure-based amendments. Similarly, the environmental credits that we claimed as certain might be difficult to access and subject to limitations, served on a first-come basis, or removed over time. Furthermore, the 20-year project duration is a long time to ensure everything goes as planned. Machine components can break before the 20 years elapse, and it might be too expensive to replace them. The GHG emission savings in our calculations only consider the destruction of methane. However, AD systems with nutrient separation units can also reduce the emissions of nitrous oxide, another potent GHG which has not been accounted for in this study. Therefore, the net external benefits calculated might be a lower-bound of actual benefits.

Policymakers must address these uncertainties if they wish to tackle the externalities associated with livestock production. One potential solution as discussed before is the utilization of high-value fiber produced by AD systems with fiber separation as a substitute for peat moss. Peat moss, although beneficial for its water-holding properties, poses environmental challenges due to the extraction and usage processes, which destroys carbon sequestering bogs and wetlands. By replacing peat moss with high-value fiber, we not only generate revenue but also mitigate secondary carbon emissions. However, it is important to note that consumers may not readily associate manure with peat moss substitutes. Even though the fiber obtained from AD is heat-treated and largely free of odor and pathogens, there is a perception among general consumers that manure products are unpleasant and contaminated. To bridge this perception gap, government intervention can play a role in raising consumer awareness and collaborating with industry leaders to certify AD fiber as a legitimate peat moss substitute. Additionally, in cases where there is limited market acceptance or absence of a market, the fiber produced can be utilized as a soil amendment in rangelands. The low moisture content of this fiber reduces transportation costs, enabling it to be transported over longer distances. By creating demand for the product in rangeland applications, farmers can be assured of a market for their product. To ensure the viability of AD systems, it is essential to establish markets for as many of their co-products as possible and enforce environmental credits. Policymakers can play a key role in facilitating this process and promoting sustainable practices within the livestock industry.

The implementation of the LCFS has been under consideration by the New Mexico legislature. This standard is already established in California, Oregon and British Columbia, Canada. The LCFS for CNG generated in New Mexico can theoretically be claimed in Oregon or California if used as transportation fuel in those jurisdictions. However, the significant cost associated with transporting such fuel and the irony of carbon emissions resulting from the process pose challenges. LCFS lowers the average carbon intensity of transportation fuels, making the transition to net-zero carbon emissions more feasible. As a result, enacting the appropriate regulations will not only help farmers produce additional cash and enhance public health, but will also aid the state in meeting its climate goals, eventually benefiting society as a whole.

This study assessed various alternatives and opportunities within the AD system from the perspective of revenue maximization for dairy farmers. In the US, when discussing AD systems, farmers often perceive them as a burden and a regulatory requirement. However, this perception should be challenged. In certain cases, AD systems have the potential to generate higher revenues compared to the dairy system itself, especially considering the narrow profit margins in the industry. While this study has utilized available information on prices and uncertainties to provide a realistic assessment of the AD system's viability, future research can delve deeper by incorporating comprehensive farm-level data. This would allow for the determination of optimal locations, sizes, and the number of AD systems to be installed in clusters, targeting areas with the highest social cost of environmental and health damages. Additionally, a lifecycle assessment of the entire supply chain would be beneficial in understanding the overall impact of greenhouse gas emissions and other environmental costs and benefits associated with AD operations. This assessment would not only identify areas for further improvement but also enable the branding of livestock as reduced carbon emitters, facilitating the marketing of products accordingly.

7. Appendix

Table A1: Parameters and variables in the Model

Parameter/Variable	Units	Values	Data source	Notes
Wet cow equivalent (x)	Milk cows	1 to 25,000	Assumed	
Discount Rate	percent	4	Assumed	
Capital lifetime	Years	20	Assumed	
Manure utilization rate	percent	90	Astill and Shumway, 2016	
Electricity price	$/kWh	0.06	https://www.eia.gov/electricity/wholesale/xls/archive/ice_electric-2021final.xlsx	Average price in 2021
CNG scrubbing rate	percent	97	Astill and Shumway, 2016	

CNG price	$/MMBTU	6.03	https://www.eia.gov/dnav/ng/hist/n3035nm3A.htm	NM avg for 2021
High value fiber price	$/Tons	165.34	Astill and Shumway, 2016	Price of peat moss replacement product, adjusted to 2021
Low value fiber price	$/Tons	25.6	https://rex.libraries.wsu.edu/view/pdfCoverPage?instCode=01ALLIANCE_WSU&filePid=13332999660001842&download=true	

Phosphates price	$/tons	103.24	Astill and Shumway, 2016	CPI adjusted to 2021
Ammonium sulfate price	S/tons	372	https://www.chemanalyst.com/Pricing-data/ammonium-sulphate-64	June 2021 price
Carbon credits price	$/MT CO2e	$22.04	https://ww2.arb.ca.gov/our-work/programs/cap-and-trade-program/program-data/cap-and-trade-program-data-dashboard	Average 2021 price in California cap and trade program

Renewable Energy Certificate (REC) price	$/ kWh	$0.20	https://www.srectrade.com/blog/srec/srec-markets/new-mexico	
Tax credit	$/ kWh	$0.02	Astill and Shumway, 2016	
Renewable Identification Number (RIN) price	$	$1.58	https://www.epa.gov/fuels-registration-reporting-and-compliance-help/rin-trades-and-price-information	Average price of qualified RIN in 2021
Low Carbon Fuel Standard (LCFS) price	$	$187.11	https://ww2.arb.ca.gov/resources/docu	Average for 2021

	ments/weekly-lcfs-credit-transfer-activity-reports

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