Anaerobic Membrane Bioreactor (AnMBR) economic viability on swine operations

by

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Abstract

Waste management in agriculture provides an important opportunity to reduce greenhouse gas emissions, recover nutrients, recycle water, and improve water quality. The objective of this study is to provide the first analysis of the economic viability of new technology for waste management – the Anaerobic Membrane Bioreactor (AnMBR). The AnMBR system utilizes biological processes to transform manure into marketable products. Previous work has analyzed the economic viability in municipal wastewater settings, but I focus on the viability for hog operations. My analysis identifies which combination of nutrient recovery systems in conjunction with the AnMBR is the most viable and the effects of government subsidies or valuing the external benefits. I focus on a comparison of the AnMBR with anaerobic digesters that have been adopted for manure management by some livestock operations. The data used represents a pilot-scale AnMBR that was designed for research purposes. A full-scale system with the capacity to treat waste from 5,000 hogs was calculated to be approximately five times the size of the pilot-scale in terms of flow-rate. I utilize net present value (NPV) to measure the viability of both pilot and full-scale systems. Assuming a 20-year useful life, a 6% discount rate, compressed natural gas (CNG) end-use for the biogas, and the ability to trade renewable identification numbers (RINs), a positive NPV was not obtained for either pilot or full-scale configurations until social benefits were considered, and the greatest NPV scenario included the AnMBR system only – no additional nutrient recovery systems. Most importantly, the configuration with the AnMBR system only was preferred to the bioreactor tank only scenario. Thus, the AnMBR system is more beneficial than the complete mix anaerobic digesters already used on farms today since the bioreactor tank is equated to a complete mix anaerobic digester

based on the potential private benefits. Finally, the subsidy scenario improved the NPV for all configurations.

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Lastly, I would like to thank Mr. Frederick Petok at the USDA and Mr. Nicholas Elger at the EPA for taking time out of their busy schedules to provide insights and data for various government programs. I hope my work will serve as an incremental progression in the research of economically feasible and environmentally beneficial manure management systems.

Dedication

My bachelor's degree was dedicated to my father, William Steven Parker. Rest in peace, Daddio. This time around, I have broken generational patterns and stepped out of family norms in faith. I hope to improve the lives of everyone I encounter, but most importantly, I hope to set my family up for success and healthy living. With that being said, I dedicate my master's thesis to the generations of stubborn Parkers that will come after me.

Wise advice from Ole Steve Parker that has carried me through: "Whatever you are, be a good one. Give everything your very level best effort, no matter what the task is. Giving up is never an option."

No discipline is enjoyable while it is happening – it is painful! But afterward there will be a peaceful harvest of right living for those who are trained in this way. So take a new grip with your tired hands and strengthen your weak knees. Mark out a straight path for your feet so that those who are weak and lame will not fall but become strong (Hebrews 12:11-13). Thank you, God, for providing me with strength and for loving me unconditionally. Your will be done.

Chapter 1 - Introduction

Ten percent of global greenhouse gas is emitted by livestock manure storage and processing (FAO n.d.) while 9% of impaired river and stream miles in the US are attributed to animal feedlots (Lugar and Leahy 1995). Excess nutrient – phosphorus and nitrogen – loads lead to eutrophication and algae blooms that decrease the oxygen levels in the water (Lugar and Leahy 1995; Huang et al. 2020). Anaerobic digesters (ADs) are sealed vessels that have been used for decades as a tool to address the negative environmental externalities caused by livestock manure management. Anaerobic digestion is a process in which bacteria transform organic matter into biogas without the presence of oxygen (USEPA 2021b). This manure management approach reduces the pollution caused by livestock waste while creating a revenue stream for the farmer by capturing the methane gas from the waste. Even so, ADs are not commonly adopted since producers perceive the costs of digester to exceed the benefits (Cowley and Brorsen 2018b). The economic feasibility of ADs on dairy and swine farms has been analyzed in previous literature using the net present value (NPV) method (Astill and Shumway 2016; Cowley, Brorsen, and Hamilton 2019; Cowley and Brorsen 2018b; 2018a; Meinen, Kephart, and Graves 2014; Bishop and Shumway 2009; Key and Sneeringer 2011; Lazarus and Rudstrom 2007; Lazarus et al. 2011; Liu 2015; Wang et al. 2011). Evidence suggests that ADs are not economically viable if private sources are the only benefits considered.

The Kansas State University Civil Engineering and Agricultural Economics departments partnered to study the technical and economic feasibility of a pilot-scale anaerobic membrane bioreactor (AnMBR) – a similar waste management technology – implemented on swine farms. AnMBRs are fairly new domestic wastewater treatment technologies. The advantage AnMBRs have over ADs is the ability to treat the liquids that run through the system. Additional advantages and revenue streams are available as nutrient recovery processes are added to the AnMBR system.

The objective of this study is to provide the first analysis of the economic viability of new technology for swine waste management – the AnMBR in conjunction with three additional nutrient recovery processes. The NPV was calculated for nine configurations of technology combinations over three policy options at the pilot and full-scale. The configuration involving the AnMBR with all three nutrient recovery processes was expected to yield the greatest NPV, but the results did not confirm this hypothesis. A positive NPV was only obtained when social benefits were considered. Moreover, the NPV was found to be more desirable for AnMBRs than complete mix ADs on swine operations assuming my bioreactor configuration equates to a complete mix AD based on private benefits. However, this assumption comes with a huge caveat that is further discussed in Chapter 2 under the "Anaerobic Membrane Bioreactor Description and Literature Review" subsection. Finally, the subsidy scenario improved the NPV for all configurations.

Chapter 2 - Anaerobic Digestion Background

Description of the Biological Component

Understanding the basic science behind anaerobic digestion (AD) will prove to be useful before discussing the economics. There is a broad range of AD systems, but in general, anaerobic bacteria are used to break down manure into biogas in the absence of oxygen (USEPA 2021b). The prokaryotic Archaea convert acetate and hydrogen from the anaerobic microbial food web reactions into methane and carbon dioxide (Rittmann and McCarty, 2020). The bacteria are further categorized by the temperatures in which they live. Mesophiles are bacteria that thrive in temperatures ranging from 30 to 42 degrees Celsius (86 to 107.6 degrees Fahrenheit), and thermophiles are bacteria that thrive in temperatures ranging from 43 to 55 degrees Celsius (109.4 to 131 degrees Fahrenheit). The efficiency of AD systems decreases when the bacteria are not in the optimal temperature range or are not fed the optimal amount and composition of organic material. Since AD is based on a biological process, there is variability in biogas generation that cannot be accurately predicted without experimental evidence for a given feedstock.

Description of the Technology

Technical efficiency of the AD system will also affect biogas production. The most commonly used systems for livestock waste management are categorized as passive, low rate, or high rate. In passive systems, biogas recovery is added to an existing treatment component. Covered lagoons are an example of passive treatment. In low-rate systems, manure flows through the digester as the main source of methane-forming microorganisms. Complete mix and plug flow digesters are examples of low-rate treatment. In high rate systems, methane-forming microorganisms are trapped in the digester to increase efficiency. Fixed film or suspended media digesters are examples of high rate treatment (Hamilton 2013).

As of September 2020, the EPA reported 263 operational AD projects on livestock farms in the U.S. Approximately 37% of the digesters are plug flow systems, 33% are complete mix, and 24% are covered lagoons (USEPA 2021a). Dairy operations have 211 digesters, of which 89 are plug flow, 72 are complete mix, and 49 are covered lagoons. Forty-five digesters are on swine operations, of which, 4 are plug flow, 16 are complete mix, and 22 are covered lagoons. Figure 2.1, along with Cowley and Brorsen (2018a) reveal that complete mix and plug flow digesters are more common on dairy operations while covered lagoons are more common on swine operations due to various engineering and economic parameters (Cowley and Brorsen 2018a).

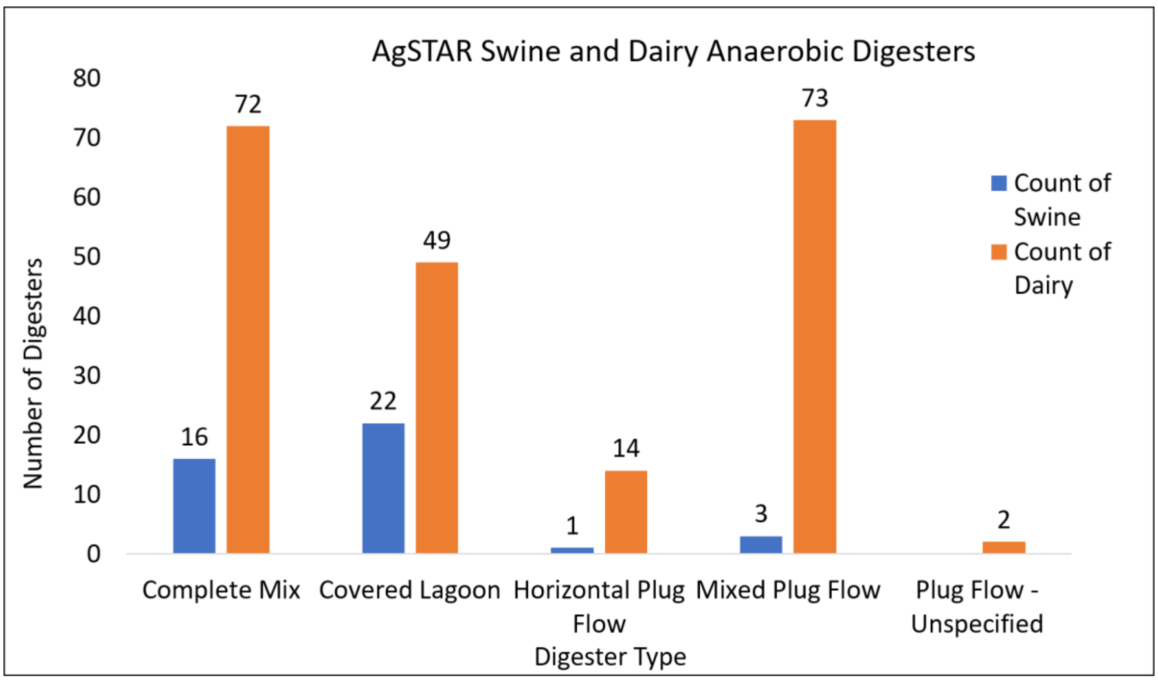

Figure 2.1 Anaerobic Digesters in the U.S. By Type and Livestock

From an engineering perspective, climate, solid content of the manure, and biogas end-use are considerations that need to be evaluated when choosing an AD system (Lim, Evans, and Parameswaran 2019; Lazarus and Rudstrom 2007; USEPA 2021b). Plug flow digesters treat manure with a high solid content of at least 10%. Biogas production increases as the solid organic material content increases (Hamilton 2013; Lazarus and Rudstrom 2007). Plug flow digesters are typically a concrete rectangular basin with a serpentine flow which allows heaters to be placed inside. This feature makes plug flow digesters ideal for cooler climates (Manning and Hadrich 2015). The same amount of manure that flows into the digester flows out of the digester and should remain for 15 to 20 days for optimal biogas production. Complete mix digesters are used for manure with a low solid content of approximately 3 to 6% solids. These digesters are typically an egg shaped or rectangular tank with a mixer and have the ability to be heated. The slurry of manure and water flow into the tank while an equal amount flows out of the tank. The solid retention time (SRT)[1] ranges from 20 to 30 days (Lazarus and Rudstrom 2007; Hamilton 2013; Hamilton 2019). Covered lagoons are earthen basins. Manure settles to the bottom while the liquid remains on top. These systems typically treat manure with low solid content and allow for a 20-year SRT (Lazarus and Rudstrom 2007; Hamilton 2013). When constructing lagoons, impenetrable liners are required to prevent contaminants from leaching into the soil and reach groundwater. Covered lagoons are better suited for arid or warm climates (Manning and Hadrich 2015; Hamilton 2013). These systems have lower capital costs and require less maintenance, but they are difficult to heat and do not optimize biogas production. See Appendix A for pictures and locations of digesters on livestock operations.

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[1] Solid retention time (SRT) is the length of time solid particles are held in the digester (Hamilton 2013).

Economic Feasibility of Anaerobic Digestion Literature Review

When considering anaerobic digestion, the primary factors affecting adoption by farmers were economic feasibility and government policies (Cowley and Brorsen 2018b). In a nationwide survey, farmers reported large capital costs and concerns of inadequate farm size were the two most common reasons for not adopting AD technology (Cowley and Brorsen 2018b). This claim is supported through previous literature that identifies high capital costs, uncertainty in environmental penalties and incentives, and uncertainty in sale prices of coproducts as the largest factors affecting AD adoption (Astill and Shumway 2016; Zaks et al. 2011; Manning and Hadrich 2015; Cowley and Brorsen 2018b). The majority of the previous studies have been case studies of low rate systems on dairy operations (Bishop and Shumway 2009; Galinato, Kruger, and Frear 2018; Lazarus and Rudstrom 2007; Stokes, Rajagopalan, and Stefanou 2008; Wang et al. 2011) with an increasing interest in swine operations and using aggregate data to simulate different scenarios (Astill and Shumway 2016; Cowley, Brorsen, and Hamilton 2019; Cowley and Brorsen 2018b; 2018a; Meinen, Kephart, and Graves 2014; Zaks et al. 2011). There is a consensus throughout the literature that ADs may be economically viable on U.S. livestock farms, but only with some combination of co-digestion[2], capital cost subsidies, and/or environmental credits (Astill and Shumway 2016; Cowley, Brorsen, and Hamilton 2019; Cowley and Brorsen 2018b; 2018a; Meinen, Kephart, and Graves 2014; Bishop and Shumway 2009; Key and Sneeringer 2011; Lazarus and Rudstrom 2007; Lazarus et al. 2011; Liu 2015; Wang et al. 2011).

[2] Dairy parlor waste, food waste, crop waste, forest waste, and other biomasses or organic materials can be used as additional feedstock for the digester when referring to co-digestion.

Net present value (NPV) has been the most common approach of evaluation. Bishop and Shumway (2009) calculated the internal rate of return (IRR) and modified internal rate of return (MIRR), Stokes et al. (2008) used a real options approach, and Wang et al. (2011) calculated the return on equity (ROE) and the return on assets (ROA) in addition to NPV. The capital and operating expenses were collected from site-specific case studies or averaged over a sample size of case studies with the exception of Cowley and Brorsen (2018ab; 2019). These publications used the same nationwide survey respondent data to extrapolate methane production and AD cost functions. The sources of uncertainty that were changed for the different NPV scenarios include: government subsidies as a percent of capital costs, carbon credits pricing and policies – California Carbon Market (CCX), European Carbon Exchange (ECX), Social Cost of Carbon (SCC), carbon cap – discount rates, useful life of technology, size of operation, type of digester, electricity purchase and sale price, and co-digestion scenarios. Although the data characteristics differ, there were generalizable findings from the literature. Electricity selling prices are too low to justify AD adoption, and it is possible the carbon markets in the U.S. have not reached the socially optimal level to reflect the SCC (Lazarus and Rudstrom 2007; Cowley, Brorsen, and Hamilton 2019; Liu 2015; Meinen, Kephart, and Graves 2014; Wang et al. 2011; Zaks et al. 2011). Moreover, Cowley and Brorsen (2018a) indicate that complete mix or plug flow digesters are more productive and cost-effective on dairy operations while passive systems, such as covered lagoons, could benefit swine operations more. It was also found that AD adoption is more practical for larger operations (Cowley and Brorsen 2018a; Cowley, Brorsen, and Hamilton 2019; Astill and Shumway 2016; Liu 2015). Furthermore, co-digestion of off-farm organic wastes allows for greater biogas production. This could create an additional revenue stream in the form of carbon credits and/or tipping fees where the farmer gets paid to dispose of wastes from different entities (Astill and Shumway 2016; C. Cowley and Brorsen 2018a; Liu 2015; Zaks et al. 2011). Other positive externalities, such as odor and water pollution reduction, have not been quantified.

Anaerobic Membrane Bioreactor Description and Literature Review

My analysis is novel because I evaluate an AnMBR on swine operations, not an anaerobic digester. Granted, both systems are similar, it is pertinent to understand the differences between them. AnMBR primary treatment tanks are similar in design to complete mix digesters that were previously discussed. Both systems are manure management systems that utilize anaerobic digestion processes. The main difference lies in the solid content of the feedstocks. AnMBRs are designed for wastewater treatment with less than 4% solids content, while ADs are traditionally designed for waste slurries with higher organic materials content. Additionally, the SRTs of the bioreactor tank ranges from 60 to 150 days while the Complete Mix AD SRT averages approximately 20 days. The longer SRT affects the growth and inoculation frequency of the bacteria. The hydraulic retention time[3] (HRT) of the bioreactor averages 11 hours while the Complete Mix AD HRT typically is the same as the SRT. The shorter HRT affects the amount of wastewater being processed. Even so, both systems are aimed at enhancing carbon sequestration in the form of biogas while greatly minimizing greenhouse gas (GHG) emissions from livestock operations. Key advantages and distinguishing features of the AnMBR platform are the ability to produce reusable water while reducing the amount of biosolids due to greater solid destruction from higher SRTs compared to AD options. Figure 2.2 summarizes the

[3] HRT is the length of time the wastewater remains in the system.

comparison. These similarities and differences establish grounds for further research into the feasibility of using AnMBRs for livestock manure management.

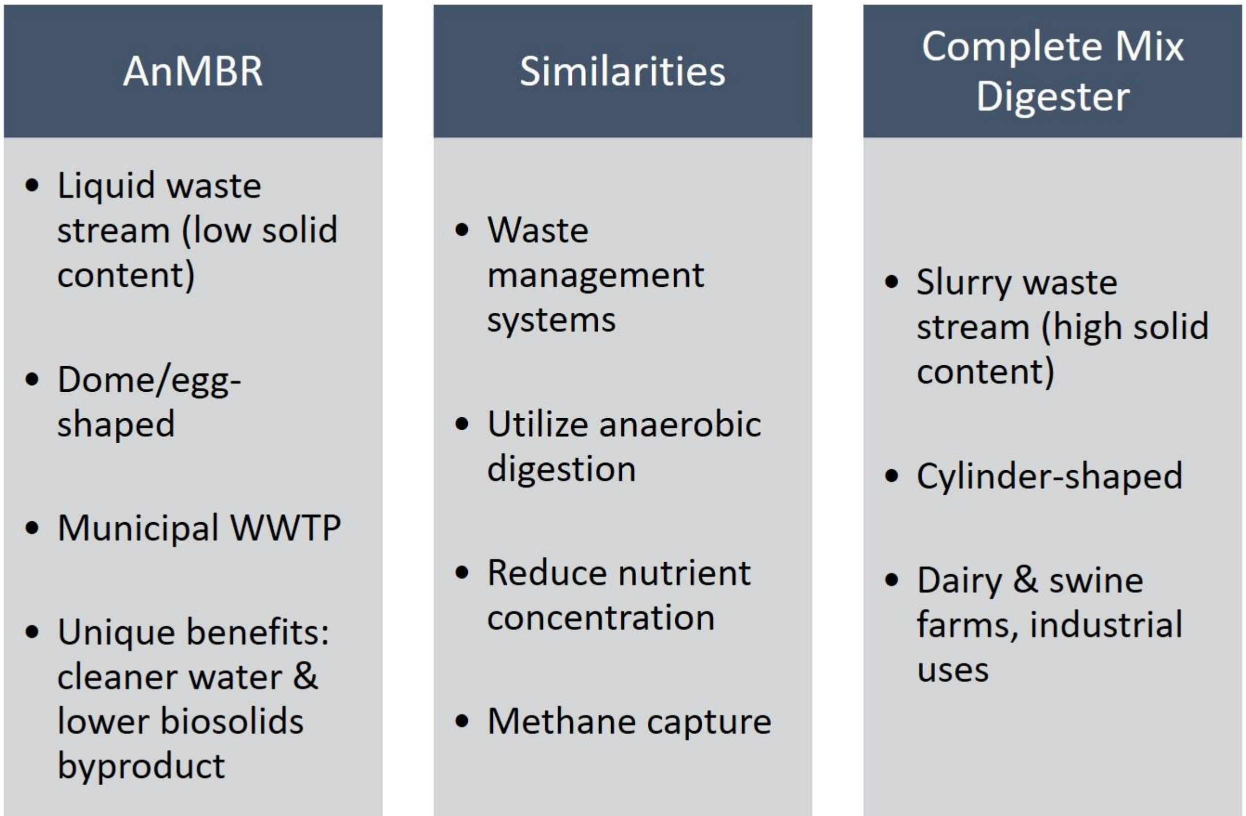

Figure 2.2 AnMBR and Complete Mix Digester Comparison

There are limited studies on AnMBRs in conjunction with nutrient recovery systems for livestock waste management. Previous literature, however, compares AnMBRs to other domestic wastewater treatments, evaluates nutrient recovery system energy efficiency, and studies the market outlook of recovered nutrients and lifecycle analyses.

When compared to existing aerobic wastewater treatment technologies, AnMBR systems focus on sustainable and economic benefits, such as: high effluent quality, minimum sludge production due to low biomass yield of anaerobic organisms, low energy demand since aeration is not required, and methane production (Pretel et al. 2014; Deng et al. 2014). Cleaning the membranes by gas sparging requires the most energy within the AnMBR system (Lim, Evans, and Parameswaran 2019; Huang et al. 2020), and is considered one of the main constraints (Pretel et al. 2014). Methane dissolved in the permeate[4] is another challenge of AnMBRs, especially during low temperature operations (Pretel et al. 2014; Deng et al. 2014). Pretel et al. (2014) suggested further development of the technologies for capturing dissolved methane to reduce the environmental impact and to enhance the economic feasibility of the AnMBR. Research is currently being conducted at Kansas State University to optimize the capturing capacity of methane dissolved within the effluent.

Nutrient control was another challenge when AnMBR technology treated domestic wastewater (Deng et al. 2014). Kansas State University researchers are also investigating this issue. Figure 2.3 illustrates the swine waste management process used at Kansas State University. The sections highlighted in green indicate the nutrient recovery systems. The pilot-scale AnMBR system on campus consists of a 300-gallon primary bioreactor tank, three membrane modules[5] for water treatment, a hollow fiber contactor for dissolved methane recovery, a coagulation-flocculation-sedimentation system for phosphorus removal, and an ion-exchange column utilizing clinoptilolite for nitrogen removal in the form of ammonia. The hog farm diverts a portion of the swine waste to a lagoon for disposal. The solids settle to the bottom allowing the water to be pumped into the AnMBR. I investigate the potential private or internal (to the swine operation itself) and external (environmental and watershed) benefits after the swine wastewater is treated by the pilot-scale AnMBR and nutrient recovery systems.

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[4] Permeate is water that has been filtered by membranes after biological or chemical treatment.

[5] Note the AnMBR system ends after the membrane modules. The following systems listed are additional nutrient recovery processes.

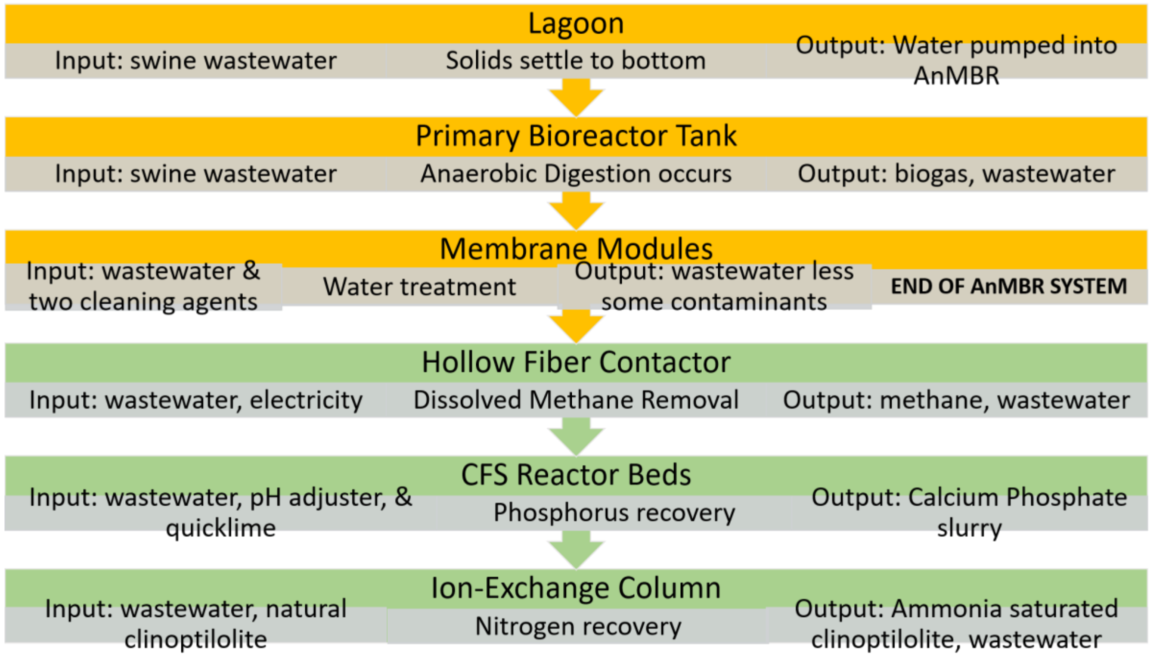

Figure 2.3 Linear Systematic View of the AnMBR and Nutrient Recovery Processes

The primary bioreactor tank stores the biogas generated from the microbes. The same pilot-scale system was used in a different study testing domestic wastewater where the biogas consisted of approximately 68% methane (Lim, Evans, and Parameswaran 2019). The percent of methane is expected to increase when testing swine wastewater due to the increased organic matter. The biogas is first used to clean the membrane modules in a process called gas sparging, then can be sold or utilized on the farm to achieve energy neutrality. The biogas can also be potentially converted to compressed natural gas (CNG) then connected to a natural gas pipeline. This option has a large cleaning, storage, and capital cost of connecting to an existing pipeline, but generally produced an increase in NPV when simulated on different scaled dairy operations if environmental credits were also received (Astill and Shumway 2016). Methane is more commonly used in combined heat and power (CHP) generation in the U.S. A combustion engine and electric generator are used to produce electricity while a heat exchanger captures excess heat from the engine (Astill and Shumway 2016). The electricity produced can be used on the farm or interconnected to the municipal grid, which also requires large fees for connection. Valuation at the Social Cost of Carbon (SCC), carbon markets, Renewable Energy Credits (REC), or Renewable Identification Number (RIN) trading under the Renewable Fuel Standards (RFS) can account for the external benefit of the reduced methane emissions. These policies will be discussed further in the policy chapter.

Nutrient Systems Description and Literature Review

Other than noting that dissolved methane removal is a challenge when implementing AnMBR systems, the literature is limited on the subject. Investigations of coagulation-flocculation-sedimentation (CFS) processes are also not very common because other forms of phosphorus recovery are more widely used, such as struvite precipitation[6] (Kehrein et al. 2020), or other forms are more efficient, such as hybrid ion exchange resins (Huang et al. 2020). Even so, it was found that phosphorus can be readily removed with coagulants (Deng et al. 2014). Phosphorus removal from the wastewater is imperative since it is such a rich source that could cause eutrophication downstream but also because of the depleting natural reserves of rock phosphate, uneven distributions, and increasing prices in recent years (Huang et al. 2020). Kehrein et al. (2020) reviewed alternative nutrient recovery systems in conjunction with AD and found that phosphorus recovered from livestock manure had the potential to fulfill the demand for phosphorus in livestock-intensive regions. They also suggested that phosphorus recovery strategies should focus on manure before municipal wastewater.

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[6] Struvite precipitation is the simultaneous removal of ammonium (N) and phosphate (P) from water solutions (Kehrein et al. 2020).

The final nutrient recovery process used is the ion-exchange column for nitrogen removal. There is extensive literature on both the technology and the media used to treat the wastewater. A natural zeolite mineral called clinoptilolite was the media of choice for the pilot-scale operations. Natural clinoptilolite is mined and is similar to clay in the sense that they are both aluminum silicates but differs from clay in its crystalline porous structure. The net negative charge and structure of the zeolite mineral allows for high cation exchange capacity[7] and is the reason it is the most commonly used zeolite mineral in agriculture (González, Faria, and Nuñez 2015; Reháková et al. 2004; Malekian, Abedi-Koupai, and Eslamian 2011; Polat et al. 2004). The benefits of clinoptilolite use in plant and animal agriculture have been studied for decades. Natural clinoptilolite used as fertilizer or soil additives increase plant yields, reduce the frequency of fertilizer application since clinoptilolite is slow releasing, reduces nitrogen leaching, act as herbicide, fungicide, and pesticide carrier, absorbs heavy metals, some pathogens, and some pharmaceuticals in the soil, buffers the soil pH, improves the long-term soil quality, and enhances the soil fertility. Natural clinoptilolite used as feed additives improves weight gain and increases feed conversion ratios in swine, poultry, and cattle. Clinoptilolite also absorbs toxins which decrease antibiotic needs and mortality due to digestive stress. Finally, clinoptilolite has also been used to decrease malodor in livestock waste and as an air purifier for poultry houses (González, Faria, and Nuñez 2015; Reháková et al. 2004; Malekian, Abedi-Koupai, and Eslamian 2011; Mumpton 1999ab; Polat et al. 2004; Nakhli et al. 2017).

[7] Cation exchange capacity is the ability for soil to hold onto positively charged micro-nutrients, such as calcium, magnesium, potassium, sodium, hydrogen, aluminum, iron, manganese, zinc, and copper (Ketterings, Reid, and Rao 2007).

Deng et al. (2014) revealed that ammonium exchange of natural zeolite could be an economical method of nitrogen removal in conjunction with AnMBRs treating domestic wastewater. The ion-exchange method would be the most complementary to the characteristics of AnMBR permeates as compared with other methods of nitrogen removal. This ammonium nitrogen concentrated in ion-exchange columns can be recovered and reused as fertilizers. They found that bottlenecks of the zeolite process would be replacing the exhausted zeolite with fresh zeolite. Another limitation is the presence of competitive cations (k^{+}, Mg^{2+}, Ca^{2+}) in the AnMBR permeate that can decrease the ammonium exchange capacity of natural zeolite (Deng et al. 2014). However, if the zeolite is recovered and reused as fertilizers, these cations could be viewed as additional micronutrients. Further studies are needed to make any suggestion for commercializing this type of modified product (Nakhli et al. 2017).

Huang et al. (2020) evaluated the economic feasibility and market opportunities of ion-exchange processes for nutrient recovery from municipal wastewater. The benefits associated with ion-exchange processes include lower costs when compared to other nitrogen recovery methods, reduction in GHG emissions when coupled with AnMBR technology, and nutrient recovery aligns with circular economy goals. However, it is not commonly used in municipal wastewater treatment due to limited media selectivity, bed clogging, and costly regenerations of spent media. It was found to be non-economical in the long run for wastewater treatment plants to dispose of the media as hazardous waste, so the recovery is critical to ensure economic feasibility. The frequency of media replacement increases the operating expenses but needs further investigation. Even after recovery of media and nutrients, challenges include the lack of viable commercialization and limited understanding of the recovered product markets.

Huang et al. (2020) conducted a study of the recovered media and recovered nutrients market. Although wastewater treatment plants had a lot of opportunity for nitrogen recovery, the industrial nitrogen synthesis approach was the cheapest option. Marketability of the recovered nutrients depends on the purity and quality of the product, the application of the product, entry points into the market, and existing substitute sale prices. For agricultural fertilizers, it is important for the recovered nutrient to consistently meet the following quality indications: greater than 95% solid content, less than 1% dust by weight, 1 – 1.25 millimeters of granular size, pathogen-free, no heavy metal contents, adequate nutrient content, and release rate that meets required levels. These fertilizers from wastewater treatment and nutrient recovery will not likely be marketed as “certified organic”. Lastly, the prices were found to vary widely due to the differing quality and purity of the products.

Kehrein et al. (2020) critically reviewed resource recovery from municipal wastewater treatment plants by focusing on the market supply, potentials, technologies, and bottlenecks. They identified nine major bottlenecks that were discussed in the literature: process costs, resource quantities, quality, market value, application and distribution, environmental emissions, health risks from potential contamination, social acceptance, and policy issues. They suggested a mindset shift for wastewater treatment plants from perceiving themselves as utilities managing a fixed budget for cost effective treatment operations to market actors producing goods. Several utilities could develop the value-chain of the same resource by acting as one supplier which would increase their collective market power and exploit economies of scale. This was put into practice in the Netherlands.

Chapter 3 - Externality Policy Discussion

Policy Theory

Methane emissions from livestock manure management can be thought of as a negative externality[8] of livestock production. Market equilibrium will not maximize net benefits to society if externalities are not addressed. All costs and benefits must be traded within a market in order to maximize net benefits to society. There are two approaches when dealing with negative externalities, assuming Pareto efficiency is the goal. The first approach is to create a market for private bargaining without government intervention. The Coase Theorem suggests that a Pareto optimal outcome will be achieved no matter how property rights are allocated if transaction fees are negligible. The definition of property rights determines the distribution of benefits. Using the manure management scenario, property rights can be defined in two ways. If the neighbors of a hog farmer have the right to clean air, the farmer could pay the neighbors based on methane emissions. If the farmer has the right to produce hogs and emissions, the neighbors could pay the farmer to relocate or reduce emissions. In practice, the Coase Theorem is difficult to implement due to vague definitions of property rights. All fifty states have Right-to-Farm Statutes that protect farmers from nuisance lawsuits (National Agricultural Law Center 2020), but loopholes of these statutes have been used to sue farmers (Runckle and Lowder 2020; Miller and Muren 2019; Washburn 2020).

The second approach of achieving a Pareto efficient outcome is through government solutions such as to permit trading a cap-and-trade system, Pigouvian taxes from policy intervention, or subsidies. In the case of manure management, the production of hogs results in

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[8] A negative externality is a cost that unintentionally falls on bystanders.

external damages – methane pollution, but it is possible to reduce, or abate, these damages at some cost. Figure 3.1 illustrates the net benefits to society from permit trading or a Pigouvian tax. MC is the marginal cost of abatement, and MB is the marginal benefits of abatement. Another way of thinking about the marginal benefits is the marginal damages reduced. A* is the optimal level of abatement while t* is the optimal permit price or the socially optimal tax per unit of emissions. Efficiency is achieved only if policy targets the damages or emissions. Permit trading creates a market for the emissions while the Pigouvian tax puts a price on the damages.

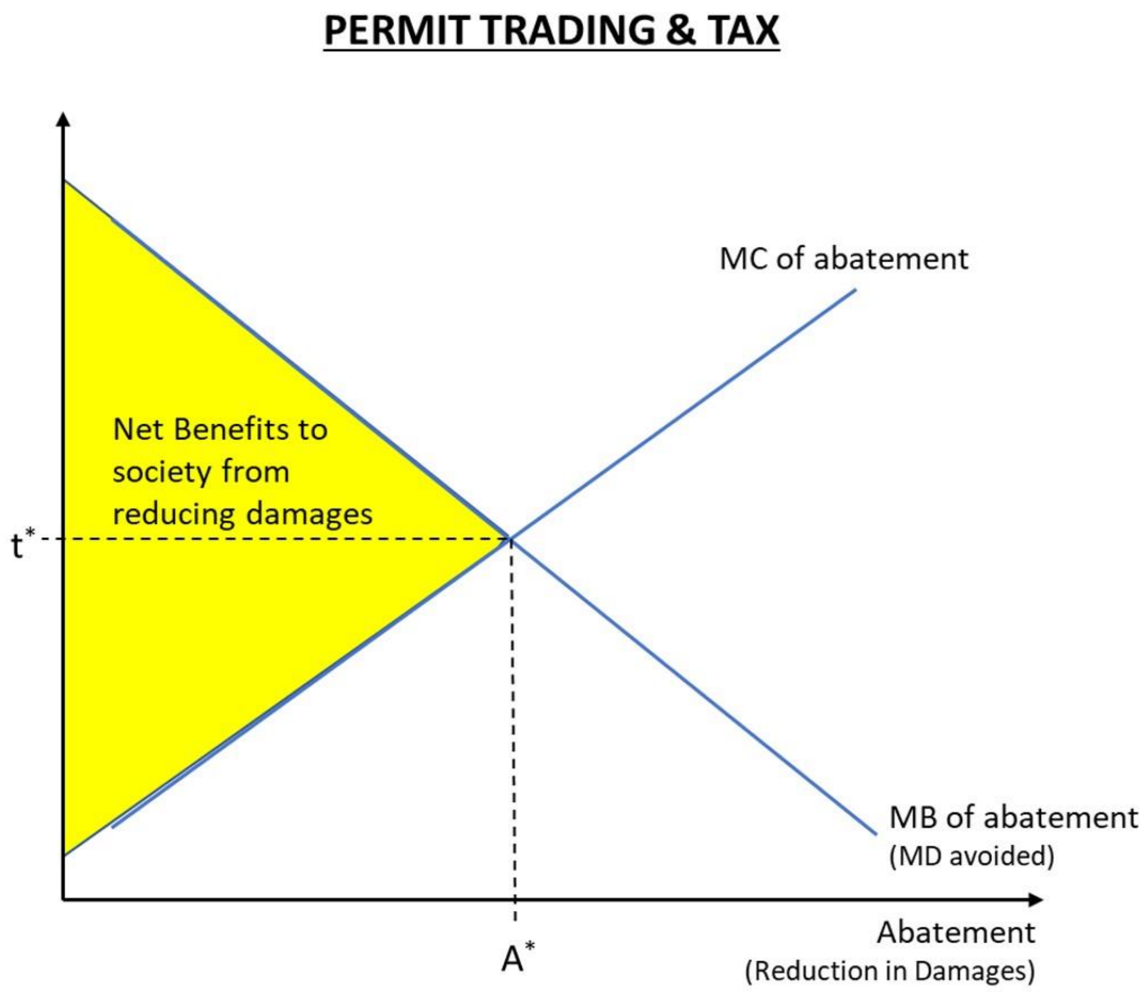

Figure 3.1 Net Benefits to Society from Permit Trading and Pigouvian Taxes

Applied Policy

RINs are an example of nationally recognized permits. The Renewable Fuel Standards (RFS) program uses renewable identification numbers (RINs) as credits or "currency". A RIN is created with a batch of renewable fuel then can be traded for use or to demonstrate compliance in the EPA moderated transaction system (USEPA 2021c). To participate in this market, the biogas, or methane, from an anaerobic digester (AD) would have to be used in a compressed natural gas (CNG) system that connects the source to an existing natural gas pipeline.

RECs are another example of nationally recognized permits. Renewable energy certificates (RECs) are tradable instruments associated with greenhouse gas emission reduction claims issued when one megawatt-hour (MWh) of electricity is generated and delivered to the electricity grid from a renewable energy resource. These were created to track renewable energy production for regulatory compliance with Renewable Portfolio Standards (RPS); however, REC markets currently exist in the United States, Europe, and Australia (USEPA 2019). To participate in this market, the biogas, or methane, from an AD would need to be processed in a combined heat and power (CHP) system.

Eleven states in the U.S. are enrolled in state-level cap-and-trade systems (Ye 2020), but there are no state or federal-level carbon taxes yet. Ten different bills have been proposed to authorize a federal carbon tax since 2018. The proposed rates range from $20 to $50 per metric ton of carbon equivalent ($MTCO_2e$) increasing at different rates each year (Columbia 2020). Kaufman and Gordon (2018) simulated the impacts of three different scenarios of a carbon tax: $14 per $MTCO_2e$ increasing by 3% annually, $50 per $MTCO_2e$ increasing by 2% annually, and $73 per $MTCO_2e$ increasing by 1.5% annually.

Payments for environmental services (PES) are programs that can be considered private or governmental solutions depending on the funding sources. Payment is made by one entity to a service provider who voluntarily agrees to provide an environmental service in an attempt to internalize an externality. The EPA is the authority of a PES specifically created to implement anaerobic digestion technology onto livestock operations. Agriculture Science to Achieve Results (AgSTAR) was launched under the Climate Change Action Plan of 1993 as a single-sector voluntary initiative that included the partnerships with the United States Department of Agriculture (USDA) to provide funding for the capital costs and the Department of Energy (DOE) to provide funding for connecting the AD to a utility or power grid. Under the USDA, funding comes from either subsidy programs, such as Renewable Energy for America Program (REAP), or cost-sharing programs, such as Environmental Quality Incentives Program (EQIP). The farmer estimates the capital costs and applies for the subsidy before the AD is even built, but the cost-sharing programs require the AD to be built before the farmer is eligible for reimbursement (USEPA 2012). In some cases, voluntary approaches may get closer to the efficient outcome than command-and-control regulations, but they are unlikely to achieve full efficiency. While they allow participants to choose the method for reaching the environmental goal, they do not establish incentives to minimize production costs (Brouhle, Griffiths, and Wolverton 2004). Consequently, voluntary agreements may create barriers to entry for non-participants and collusive behavior through phasing out products or price setting. To find the average cost of reducing one metric ton of carbon dioxide equivalent, I created a dataset using the AgSTAR database for methane emissions data and project reports for capital cost and government funding data. On average, the funded projects enrolled in AgSTAR required $135 of government funding to reduce one metric ton of carbon dioxide equivalent per year, and only

34% of the projects' capital costs were covered by government grants. Nation-wide survey results with eight swine producer respondents revealed that 53% of capital costs are subsidized for complete mix digesters, but approximately 75% of capital costs need to be subsidized to break even (C. Cowley and Brorsen 2018a).

Chapter 4 - Methods

Overview

Capital budgeting typically uses the net present value (NPV) method as one tool to compare and determine the viability of investments. NPV determines the current value of all future cash flows associated with the investment. Previous literature applies this method to measure the economic feasibility of ADs on dairy and swine operations (Astill and Shumway 2016; Bishop and Shumway 2009; Cowley, Brorsen, and Hamilton 2019; Cowley and Brorsen 2018b; 2018a; Galinato, Kruger, and Frear 2018; Lazarus and Rudstrom 2007; Manning and Hadrich 2015; Stokes, Rajagopalan, and Stefanou 2008; Wang et al. 2011; Zaks et al. 2011). The standard NPV decision rule is to adopt if NPV is greater than zero, but in the case of waste management, a negative NPV could be optimal since it does not account for other profitable aspects of the swine operation. For this reason, the NPV decision rule used for this analysis is to adopt the option with the greatest NPV.

My analysis follows the framework and structure of Manning and Hadrich (2015). Their analysis evaluated the private gross benefits, social gross benefits, subsidized private costs, unsubsidized private costs, and NPV of ten different dairy operations in terms of electricity used and produced. Each equation was dependent on the number of cows on the farms. In the case of the AnMBR, each equation is dependent on the flow rate of the system due to the differences in technology. Nine configurations of technology combinations over three policy options at the pilot and full-scale were simulated using the same equations as Manning and Hadrich (2015). Compressed natural gas (CNG) with renewable identification number (RIN) trading was the assumed biogas end use. The notation for each configuration indicates which systems were included in the NPV calculations. All scenarios include the bioreactor tank, bioprocess tank insulation, online startup, and commission fee, and the remote access module lease as part of the capital costs. The membrane modules have a useful life of ten years, and the dissolved methane hollow fiber contactor has a useful life of five years. The replacement costs are accounted for in the operating costs of the appropriate scenarios that incorporate these processes. As systems are added to the simulation, additional inputs and outputs are added as well. The operating costs of the AnMBR include electricity without dissolved methane (DM) recovery, sodium hypochlorite, and citric acid for cleaning the membranes. Private benefits of the AnMBR include biogas without DM removal, RINs without DM removal, and water recovered. Social benefits of the AnMBR include water quality improvement, odor reduction, and greenhouse gas (GHG) emissions reduction valued at the SCC without DM removal. When the DM removal process is added to the AnMBR, this changes the electricity operating cost, biogas private benefit, RIN private benefit, and GHG mitigation social benefit. The coagulation-flocculation-sedimentation (CFS) process used to remove phosphorus (P) requires quicklime as a medium and hydrochloric acid for pH balance. The private benefit of the CFS process is the phosphorus slurry that can be sold as a fertilizer. The ion-exchange process requires natural clinoptilolite as a medium, and the private benefit is the nitrogen enriched product that can also be sold as a fertilizer. The BR scenario simulated the bioreactor tank for biogas recovery only. Other than the replacement costs of membrane modules and the dissolved methane hollow fiber contactor, all operating costs and benefits are held constant over time. Table 4.1 lists the configurations and private benefits associated with each. See Appendix C for a summary of capital costs, operating costs, private benefits, and social benefits for each of the nine configurations and examples of NPV calculations for pilot and full-scales.

Table 4.1 Configurations and Associated Private Benefits

AnMBR+DM+P+N	• Methane gas & water + dissolved methane + phosphorus + nitrogen
AnMBR+DM+P	• Methane gas & water + dissolved methane + phosphorus
AnMBR+DM+N	• Methane gas & water + dissolved methane + nitrogen
AnMBR+DM	• Methane gas & water + dissolved methane
AnMBR+P+N	• Methane gas & water + phosphorus + nitrogen
AnMBR+P	• Methane gas & water + phosphorus
AnMBR+N	• Methane gas & water + nitrogen
AnMBR	• Methane gas & water
BR	• Methane gas

Private Benefits

The farmer will compare the private benefits to the private costs when considering adoption. As illustrated in Table 1, the benefits will differ depending on which processes are adopted in conjunction with the AnMBR. This evaluation assumes all products have buyers, and the transaction and transportation fees do not fall on the farmer. The private gross benefits (GBp) of each configuration are represented by Equation 1 – the present value of expected private benefits from the entire 20-year useful life. Table 3 describes each variable.

Equation 4.1 Private Gross Benefits

$$GBp_i = \sum_{t=0}^{T} \frac{\lambda_i(\Omega)\mathrm{p}^{\lambda} + \alpha(\Omega)\mathrm{p}^{\alpha} + \delta(\Omega)\mathrm{p}^{\delta} + \Upsilon(\Omega)\mathrm{p}^{\Upsilon} + \varepsilon_i(\Omega)\mathrm{p}^{\varepsilon}}{(1+r)^t}$$

Table 4.2 Pilot-Scale Private Gross Benefits

NOTATION	DESCRIPTION	QUANTITY	ANNUAL VALUE ($/YR)
Ω	Wastewater (ww) treated per year[a]	255,500 gal ww/yr 967,250 L ww/yr 821.25 m^3 ww/yr	-
$\lambda_1(\Omega)$	Biogas sold as compressed natural gas (CNG) – including DM[b]	4.34 MMBTU CH_4/yr	$28.92/yr
$\lambda_2(\Omega)$	Biogas sold as compressed natural gas (CNG) – excluding DM[b]	7.47 MMBTU CH_4/yr	$16.78/yr
p^{λ}	Price of CNG[b]	$3.87/MMBTU CH_4	-
$\alpha(\Omega)$	Recovered phosphorus fertilizer[c]	2.205 X10^{-7} ton/yr	$18.82/yr
p^{α}	Price of recovered P fertilizer[d]	$88.24/ton	-
$\delta(\Omega)$	Recovered nitrogen fertilizer[e]	4.87 tons/yr	$476.85/yr
p^{δ}	Price of recovered N fertilizer[f]	$98/ton	-
ϒ	Quantity of water recovery[g]	255,500 gal/yr	$2,555/yr
p^{Υ}	Price of water recovered[h]	$0.01/gallon	-
$\varepsilon_1(\Omega)$	Permit Trading including DM – RINs[i]	194.998 RIN/yr	$208.65/yr
$\varepsilon_2(\Omega)$	Permit Trading excluding DM – RINs[i]	113.10 RIN/yr	$121.21/yr
p^{ε}	Price of RINs[i]	$1.07/RIN	-
r	Discount rate[j]	6%	-
t	Useful life[k]	20 years	-

a. 700 gallons ww/day = 2,650 L ww/d = 2.25 m^3 ww/d (Expert opinion of Prathap Parameswaran).
b. Represents 52% volume of the pre-scrubbed methane generated; DM is shorthand for the Dissolved Methane recovery process (Astill and Shumway, 2016; Coppedge, et al., 2012).
c. 0.20 g P/L ww (Expert opinion of Evan Heronemus).
d. Slow-release P source (Astill and Shumway, 2016; Promous Energy, 2014).
e. 40 pounds of Clinoptilolite every 1.5 days (Expert opinion of Prathap Parameswaran).
f. Recovered ammonium sulfate slurry (Astill and Shumway, 2016; Promous Energy, 2014).
g. Flow rate per day multiplied by 365 day: 700 gal/d * 365 d
h. Astill and Shumway, 2016
i. RINs are used in conjunction with CNG end use. 0..48 RIN/m^3 CH_4 (Astill and Shumway, 2016; Coppedge, et al., 2012; Weisberg, 2015).
j. Cowley and Brorsen, 2019
k. Harclereode, Doody, Brower, et al., 2020

Private Costs

The private costs of traditional anaerobic digestion include the initial investment, or capital costs, the financing, and the operating expenses (Manning and Hadrich 2015); however, financing is not included in my analysis. Equation 2 defines the private costs of the configurations, and Table 4 describes each variable for the pilot-scale.

Equation 4.2 Private Costs

$$PC_i = \Theta d(\Omega) + \sum_{t=0}^{T} \frac{e_i(\Omega)\mathrm{p}^e + \beta^{SOD}(\Omega)\mathrm{p}^{SOD} + \beta^{CIT}(\Omega)\mathrm{p}^{CIT} + \beta^{HYD}(\Omega)\mathrm{p}^{HYD} + \beta^{LIM}(\Omega)\mathrm{p}^{LIM} + \beta^{CLI}(\Omega)\mathrm{p}^{CLI}}{(1+r)^t}$$

Table 4.3 Pilot-Scale Private Costs

NOTATION	DESCRIPTION	QUANTITY	ANNUAL COST ($/yr)
d(Ω)	Capital costs[a]	Varies depending on scenario.	-
Θ	Share of capital investment paid by the farmer[b]	0.47	-
Ω	WW treated per year[c]	255,500 gal ww/yr 967,250 L ww/yr 821.25 m^3 ww/yr	-
e_1	Electricity consumed by pumps – including DM[d]	0.349 kWh/m^3 286.62 kWh/yr	$28.66/yr
e_2	Electricity consumed by pumps – excluding DM[d]	0.341 kWh/m^3 280.05 kWh/yr	$28.00/yr
p^e	$0.10/kWh[e]	-	-
$\beta^{SOD}(\Omega)$	Operating cost of sodium hypochlorite – cleaning	250 mg NaOCL/L ww 241.81 kg NaOCl/yr	$53.20/yr
p^{SOD}	$0.22/kg[f]	-	-
$\beta^{CIT}(\Omega)$	Operating cost of citric acid – cleaning	193.45 kg $C_6H_8O_7$/yr	$354.01/yr
p^{CIT}	$1.83/kg[f]	-	-
$\beta^{HYD}(\Omega)$	Operating cost of hydrochloric acid – pH adjustment	19.35 kg HCl/yr	$338.54/yr
p^{HYD}	$17.50/kg[g]	-	-
$\beta^{LIM}(\Omega)$	Operating cost of quicklime – P recovery	386.90 kg Quicklime/yr	$42.56/yr
p^{LIM}	$0.11/kg[f]	-	-
$\beta^{CLI}(\Omega)$	Operating cost of clinoptilolite – N recovery	4.87 tons Clinoptilolite/yr	$974.00/yr
p^{CLI}	$200/ton[h]	-	-

a. (Intuitech, 2015); see Table 6 or Figure 1.
b. On average, 53% of capital costs of complete mix digesters on swine farms were covered by government grants (Cowley, 2015). 100% - 53% =47% paid by farmer.
c. 700 gallons ww/day = 2,650 L ww/d = 2.25 m^3 ww/d (Expert opinion of Prathap Parameswaran).
d. DM is shorthand for Dissolved Methane recovery process (Lim, Evans, and Parameswaran, 2019)
e. https://www.eia.gov/electricity/sales_revenue_price/
f. Table S5 of Supporting Information (Harclerode, Doody, Brower, et al., 2020)
g. Current market price ranges from $50 to $70/gallon, or $12.50 to $17.50/kg.
h. Current market price of granular, naturally mined clinoptilolite ranges from $145 to $210/ton.

Social Costs and Benefits

In general, the social cost is equal to the private costs plus the external costs. The social cost of the AnMBR and nutrient systems is equal to the unsubsidized private cost. In general, the social benefit is equal to the private benefit plus the external benefit. The AnMBR social gross benefits (GBs) include odor reduction, GHG abatement, and water quality improvement. Astill and Shumway (2016) took the approach of valuing odor reduction as cost-savings of avoiding an odor related nuisance lawsuit. GHG abatement was calculated and valued at the EPA's 2020 SCC (USEPA 2016). Equation 3 demonstrates the conversions used to estimate the methane emissions estimate. In a previous study, the pilot-scale AnMBR system yielded 0.14 liters of methane per gram of chemical oxygen demand (COD) that was fed into the system (Lim, Evans, and Parameswaran 2019). Granted, domestic wastewater was used in the previous study, the reported value is used as an indicator of the methane recovery efficiency. Three grams of COD per liter of wastewater is a professional estimated[9] characteristic of a medium concentration of swine wastewater. The density of methane gas at 0 degrees Celsius is 0.54 kilograms of methane per one cubic meter of methane. After estimating the metric tons of methane per liter of wastewater, this was multiplied by liters of wastewater per year. To account for the scenarios that exclude dissolved methane capture, the metric tons of methane per year was multiplied by 58% since 42% of methane was dissolved in the permeate during the previous project using the pilot-scale AnMBR (Lim, Evans, and Parameswaran 2019). The estimated annual methane produced per year was then multiplied by 25 for the metric tons of carbon dioxide equivalent per year to reflect that one ton of methane over 100 years is 25 times the forcing as compared to one ton of carbon dioxide over the same time (Manning and Hadrich 2015).

Equation 4.3 Greenhouse Gas Abatement Estimation

$$\frac{0.14\ L\ CH_4}{g\ COD}\ X\ \frac{3\ g\ COD}{L\ ww}\ X\ \frac{m^3\ CH_4}{1{,}000\ L\ CH_4}\ X\ \frac{0.54\ kg\ CH_4}{m^3\ CH_4}\ X\ \frac{1\ MT\ CH_4}{1{,}000\ kg\ CH_4} = \frac{2.27\ X\ 10^{-7}\ MT\ CH_4}{L\ ww}$$

[9] Christopher Chiu – AnMBR operator and dissolved methane expert.

$$\left(\frac{2.268\ X\ 10^{-7}\ MT\ CH_4}{L\ ww}\ X\ \frac{L\ ww}{year}\right) * 25\ =\ \frac{MTCO2e}{year}$$

There are limited studies that place a dollar value on water quality improvement that are useful for my analysis. Egan et al. (2009) attempt to value water quality in Iowa lakes as a function of water quality measures. Functional models were tested over several scenarios, then the compensating variation (CV) was calculated for each model and scenario. $19.45 per household was the CV extrapolated from the most credible model that simulated water quality improvement of nine regional lakes in Iowa to the standards of the cleanest lake in the entire state. Equation 4 demonstrates the approach I used to find the value of improvement per hog associated with reducing nitrogen pollution by 76%, ceteris paribus, or reducing phosphorus pollution by 77%, ceteris paribus. The USDA reported swine production contributing approximately 30% of the total agriculture sales in Iowa (USDA 2017); thus, 0.3 represents the share of water pollution attributed to swine production in Iowa. The population of hogs in Iowa was reported by the National Agricultural Statistics Service (USDA 2021).

Equation 4.4 Water Quality Improvement Value per Hog

$$\frac{(\$\,19.45/household\ *\ 1{,}265{,}473\ households\ *\ 0.3)}{24{,}800{,}000\ hogs}\ =\ \$\,0.03/hog$$

Social benefits are private benefits plus external benefits. Equation 5 depicts the social gross benefits of the AnMBR and nutrient recovery systems. Table 5 defines the external benefit variables.

Equation 4.5 Social Gross Benefits

$$GBs_i = \sum_{t=0}^{T} \frac{\lambda_i(\Omega)\mathrm{p}^{\lambda} + \alpha(\Omega)\mathrm{p}^{\alpha} + \delta(\Omega)\mathrm{p}^{\delta} + \Upsilon(\Omega)\mathrm{p}^{\Upsilon} + \phi + \mu + \pi_i\mathrm{p}^{\pi}}{(1+r)^t}$$

Table 4.4 Pilot-Scale External Benefits

NOTATION	DESCRIPTION	VALUE REPORTED	ANNUAL BENEFIT ($/yr)
$\boldsymbol{\varphi}$	Odor reduction/cost-savings in an event of a lawsuit for odor[a]	$100/d	$36,500.00/yr
$\boldsymbol{\mu}$	Water Quality Improvement[b]	$0.03/hog	$47.64/yr
$\boldsymbol{\pi_1}$	Greenhouse gas abatement – including DM[c]	5.6575 $MTCO2_e$/yr	$237.62/yr
$\boldsymbol{\pi_2}$	Greenhouse gas abatement – excluding DM[c]	3.285 $MTCO_2e$/yr	$137.97/yr
$\mathrm{p}^{\boldsymbol{\pi}}$	Social Cost of Carbon (SCC)[d]	$42/$MTCO_2e$	-

a. $100/d * 365 days/yr (Astill and Shumway, 2016).
b. 160 sows on the Kansas State University hog farm.
c. DM is shorthand for Dissolved Methane recovery process.
d. USEPA 2016

The NPV was calculated for each configuration over three different policy scenarios. First, the present value difference between GBp and the unsubsidized PC was calculated. This policy scenario simulated permit trading with Renewable Identification Numbers (RINs) in conjunction with compressed natural gas (CNG). Second, the present value difference between GBp and the subsidized PC was calculated. This policy scenario simulated both permit trading and a 53% subsidy (C. Cowley and Brorsen 2018a). Third, the present value difference between GBs and the unsubsidized PC, or SC, was calculated. This policy scenario simulated society's benefits from AnMBR adoption on one swine operation. See Appendix C for the capital costs of each configuration and an example of the NPV using the AnMBR+DM+P+N configuration over the permit trading policy scenario.

Scaling Estimations

The purpose of the pilot-scale analysis was to establish a base evaluation for further investigation. It would, however, be inappropriate to compare the pilot-scale results to previous literature on AD economic feasibility, but the alternative municipal scale AnMBRs used to treat domestic wastewater in highly populated cities would also be inappropriate to compare to previous studies on traditional ADs. Several scaling methods were attempted, all proving to have drawbacks. The following describes my preferred scaling method to achieve a capital cost estimation for an AnMBR capacity of 5,000 hogs[10].

Table 4.5 Cost per Unit of Volume for Pilot, Full, and Municipal Scales

System	Volume (gallon)	Total Capital Cost ($)	Cost per Unit Volume ($/gal)
Pilot Scale[a]	343.42	$277,944.00	$809.33
Full Scale AD[b]	104,612.15	$208,623.58	$1.99
Municipal Scale AD[c]	295,209	$640,000.00	$2.17
Municipal Scale AnMBR[c]	1,274,380	$3,050,000.00	$2.39

a. Lim, Evans, and Parameswaran, 2019
b. 5,000 head operation (Meinen, Kephart, and Graves, 2014)
c. Evans, Brower, Doody, et al., 2018 (page 881 and 875)

A case study of a 4,800 head swine operation reported 104,612.15 gallons of available volume in the empty AD (Meinen, Kephart, and Graves 2014). Thus, the goal volume for a full-scale AnMBR would approximately be a 100,000-gallon tank. Note that this volume is likely larger than needed to treat the swine wastewater using an AnMBR. ADs treat higher solid content wastes of about 10% while the AnMBR treats wastes with less than 4% solid content. Lower solid content and a higher flow rate suggest the AnMBR tank would not have to be as

[10] According to the USDA, operations with 5,000 head or more provide over 90% of the market's supply of hogs in the U.S.

large as the traditional digester. Aside from the pilot-scale, the systems cost around $2.00 per gallon of available volume which indicated the possibility of using this metric as a scaler to find the capital costs of a full-scale AnMBR. I multiplied $2.39 per gallon of available municipal scale volume by the goal reactor volume of 100,000 gallons for approximately $240,000 full-scale bioreactor tank capital cost. Since the rest of the systems depend on the flow rate, a different scaling factor was used. The pilot-scale flow rate was 2,650 liters of wastewater per day, and the flow rate reported by Meinen, Kephart, and Graves (2014) was 14,160 liters of wastewater per day. The quotient of the two flow rates, approximately 5, was used as a scaling factor for the membrane modules, ion-exchange process, CFS process, methane contactor process, and tank insulation. The steel trailer cost and the shipping estimate were not scaled because the full-scale bioreactor tank was based on a concrete structure. The online startup and commissioning fee and the remote access module lease were estimated to be equal for both the pilot and full-scale. Table 7 summarizes the pilot and scaled costs.

Table 4.6 Scaled Capital Costs

Component	Pilot Scale Costs	Full-Scale Costs
Modified Container (Steel Trailer)	$105,938	-
Bioreactor Tank (Intuitec - Membrane Cost)	$277,944	$240,000
Membrane Modules (Final Report * 3 Modules)	$3,523	$18,672
Ion Exchange Process (N Recovery)	$7,568	$40,110
CFS Process (P Recovery)	$31,510	$167,003
Methane Contactor Process (Dissolved CH4)	$21,443	$113,648
Bioprocess Tank Insulation	$3,000	$15,900
Shipping Estimate	$3,500	-
Onsite Startup and Commissioning	$11,417	$11,417
Remote Access Module Lease	$2,000	$2,000

Chapter 5 - Results

Private Capital Costs

The results are reported for the nine configurations over three policies at the pilot and full-scale. The capital costs are the largest expense to the producer and have been a limitation of adoption for ADs on many farms. The pilot-scale bioreactor tank accounts for 54% of the total capital expenses because it was custom-made for research. Other pilot costs may be inflated for the same reason. The second largest capital expense was the steel trailer that accounted for 21% of total capital costs. The expectation of confining the AnMBR and nutrient systems into the steel tank was to run the system year-round. Typically, the mesophyll bacteria used in the bioreactor tank produce very little methane during cooler temperatures. After scaling, the bioreactor tank constructed from concrete represents only 28% of the capital expenses. The second largest portion is represented by methane contactor replacement costs that account for 27% of the total. This system needs to be replaced every five years (Harclerode et al. 2020). Since the full-scale costs were scaled from the pilot-scale, it is likely these capital expenses are over-estimated.

Social Benefits

Figure 5.3 breaks down the present value of the pilot-scale total benefits for three configurations. Total benefits are equal to gross private and gross social benefits. The three configurations include the AnMBR system with all three nutrient recovery processes, the AnMBR system only, and the bioreactor tank only. PB is shorthand for private benefits. SB is shorthand for social benefits. WQI is shorthand for water quality improvement. Odor reduction is the largest portion of benefits. The reusable water is the second largest share of benefits for the configurations that include the membranes. The purpose of this graph is to compare the marginal benefits of water recovery (difference between AnMBR and BR) and nutrient recovery (difference between AnMBR+DM+P+N). The addition of membranes that recover water has a larger marginal benefit than the addition of nutrient recovery processes. The full-scale benefits follow the same pattern.

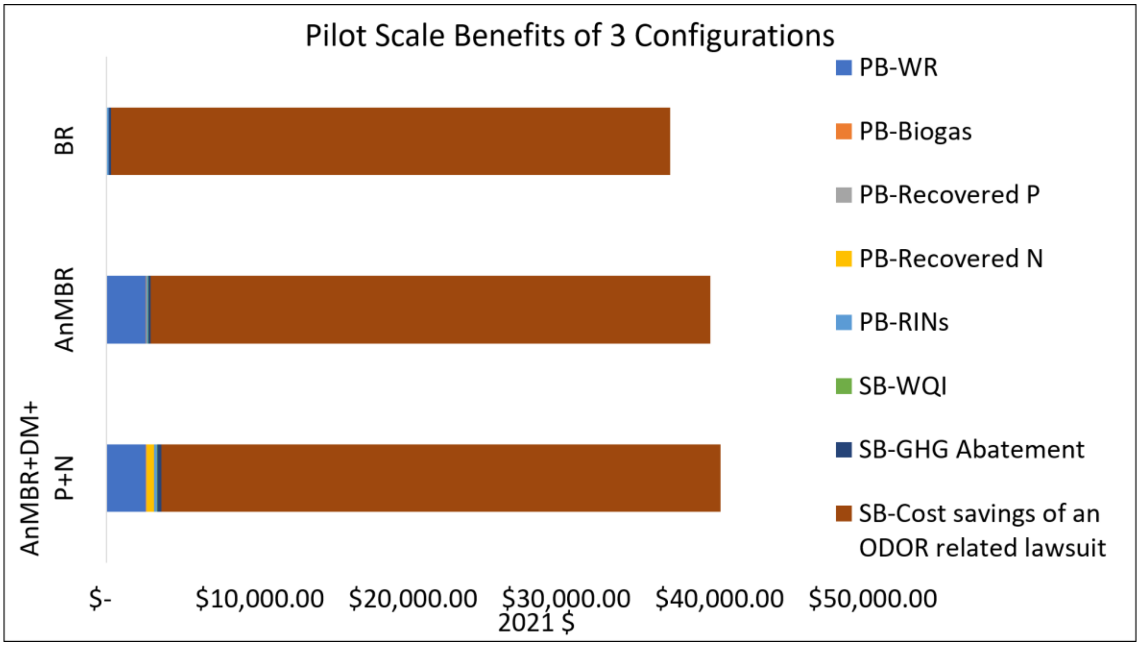

Figure 5.1 Pilot-Scale Benefits of 3 Different Configurations

Net Present Value of the Pilot and Full-Scale

Figure 5.4 is a graphical representation of the pilot-scale NPV of all nine configurations over the three policy options. The NPV does not become positive unless the social benefits are accounted used in the calculations. This means the AnMBR with nitrogen recovery, AnMBR system only, and the bioreactor tank only are the only configurations that benefit society. There are no positive NPV options that only account for private benefits, even when the private costs are subsidized. The greatest NPV is realized when all social benefits are accounted for in the AnMBR only scenario.

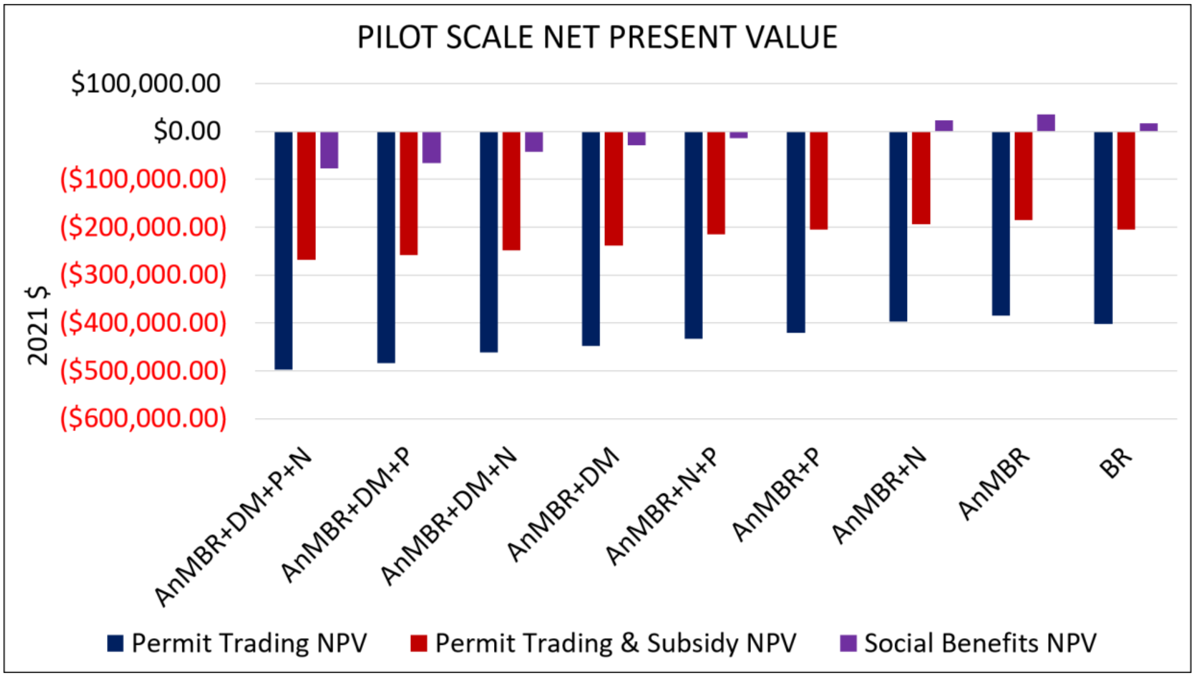

Figure 5.2 Pilot-Scale Net Present Value

Table 5.1 Pilot-Scale Net Present Values

SYSTEM	Permit Trading NPV	Permit Trading & Subsidy NPV	Social Benefits NPV
AnMBR+DM+P+N	($497,374.41)	($268,131.34)	($77,843.57)
AnMBR+DM+P	($484,104.13)	($258,569.38)	($66,047.59)
AnMBR+DM+N	($461,709.08)	($247,905.91)	($42,178.23)
AnMBR+DM	($448,438.81)	($238,343.96)	($28,908.07)
AnMBR+N+P	($433,435.45)	($214,699.45)	($14,044.78)
AnMBR+P	($420,165.29)	($205,137.61)	($774.51)
AnMBR+N	($397,770.13)	($194,474.03)	$22,722.15
AnMBR	($384,499.97)	($184,912.19)	$34,890.82
BR	($402,537.42)	($204,675.91)	$16,306.82

Figure 5.5 is a graphical representation of the full-scale NPV of all nine configurations over the three policy options. Same as the pilot-scale, the NPV does not become positive unless the social benefits are accounted used in the calculations. Unlike the pilot-scale, the NPV is positive for all social benefit options that do not include dissolved methane recovery. This means

the AnMBR with nitrogen and phosphorus recovery, AnMBR with phosphorus recovery, AnMBR with nitrogen recovery, AnMBR system only, and the bioreactor tank only are the configurations that benefit society. There are no positive NPV options that only account for private benefits, even when the private costs are subsidized. Same as the pilot-scale, the greatest NPV is realized when all social benefits are accounted for in the AnMBR only scenario.

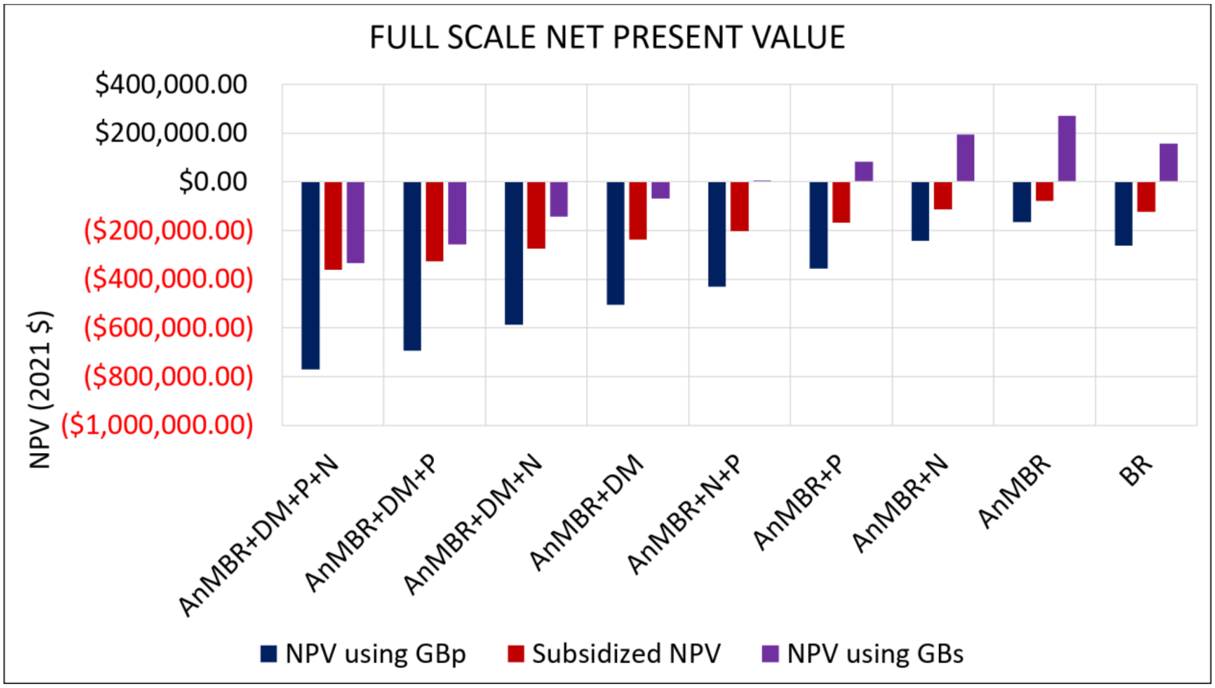

Figure 5.3 Full-Scale Net Present Value

Table 5.2 Full-Scale Net Present Values

SYSTEM	Permit Trading NPV	Permit Trading & Subsidy NPV	Social Benefits NPV
AnMBR+DM+P+N	($770,132.74)	($361,962.39)	($332,876.40)
AnMBR+DM+P	($694,195.75)	($326,272.00)	($256,939.42)
AnMBR+DM+N	($586,021.61)	($275,430.16)	($143,669.81)
AnMBR+DM	($504,989.16)	($237,344.91)	($67,732.83)
AnMBR+N+P	($431,298.34)	($202,710.22)	$5,303.75
AnMBR+P	($355,361.24)	($167,019.78)	$81,240.74
AnMBR+N	($242,091.76)	($113,783.13)	$194,510.34
AnMBR	($166,154.77)	($78,092.74)	$270,447.32
BR	($262,881.23)	($123,554.18)	$156,645.36

Chapter 6 - Discussion and Conclusions

Stakeholders[11] of the Kansas swine industry were interviewed to gain insight into the reality of swine manure management. After a brief description of the AnMBR and nutrient recovery systems, the stakeholders were asked to identify initial hesitations and to identify the most beneficial aspects. The limitations of full-scale cost data, product markets that are not established, and management concerns were the most prominent hesitations. All stakeholders were in agreement that the most appealing aspect was the ability to move captured nutrients, especially phosphorus, off the farm, assuming no other issues were created in the process. Farmers expressed the difficulty of staying under the phosphorus load limits and their concerns of preventing a water quality issue in their area. However, the nutrient management solution must be economically feasible for farmers to adopt these practices. An alternative to recovering nutrients considered by the stakeholders is purchasing land to increase the total nutrient load limits. This insight suggests that the market price of phosphorus used in my analysis did not fully capture the recovered nutrient value from the farmer's perspective. Moreover, stakeholders suggested that it may be more feasible to market the recovered water for on-farm uses instead of trying to achieve potable water quality. The public perception of recovered water is negative while there continues to be controversy of health risks among legislators. Even with long-term data indicating consistently safe water quality, legislation may not get passed. I kept the recovered water in my analysis as a private benefit to achieve an estimation of all potential

[11] Stakeholders interviewed included two Kansas swine producers, a manager from Kansas Department of Agriculture, a Kansas Department of Health and Environment livestock waste specialist, the Chief Executive Officer of the Kansas Pork Association, and two sustainable environmental consultants.

benefits from the AnMBR and nutrient recovery systems but the stakeholder insight suggests that policy regulations need to be changed before recovered water can be sold.

The net present value (NPV) was greater than zero in a few configurations that used social gross benefits for both the pilot and full-scales. The government policy option that significantly improved the NPV for all systems was the subsidy as a percent of the total costs. The scenario that resulted in the greatest NPV was the AnMBR system alone without any additional nutrient recovery systems. This finding did not confirm the original hypothesis. The AnMBR only scenario had lower operating costs than all other scenarios that implemented additional nutrient recovery processes. The BR only scenario was the only one that had lower operating costs than the AnMBR only scenario; however, the bioreactor is designed to treat water with lower solid content compared to traditional ADs. This means the bioreactor is not as efficient at producing methane compared to traditional ADs. The BR only scenario also loses the water recovery private benefit and water quality improvement social benefit. The lower capital and operating costs of the BR only scenario were not enough to offset the lower total gross benefits.

Even though the BR tank is comparable to a complete mix digester, the results from the AnMBR configurations cannot be compared to previous literature. The complete mix digester market is already established while the AnMBR system is still in the research phase of development. Factors that affect the AnMBR NPV include the shorter useful life than traditional ADs, scaling difficulties, and technology research and development.

Further investigation of full-scale capital costs for AnMBRs and nutrient recovery systems would be beneficial to determine the economic viability. After these costs are established, it would be interesting to see how different prices for the recovered nutrients and

RINs would change the NPV as well as what the SCC would have to be in order to break even. Furthermore, the valuation of water quality improvement warrants investigation since this factor is what separates the AnMBR from traditional manure management methods.

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Appendix A - Pictures and Locations of Low Rate Anaerobic Digesters

Figure A.1 shows the full-scale complete mix AD that my calculations were based on. The pilot-scale bioreactor tank is over 300 times smaller than the digester in Figure A.1 in terms of available volume.

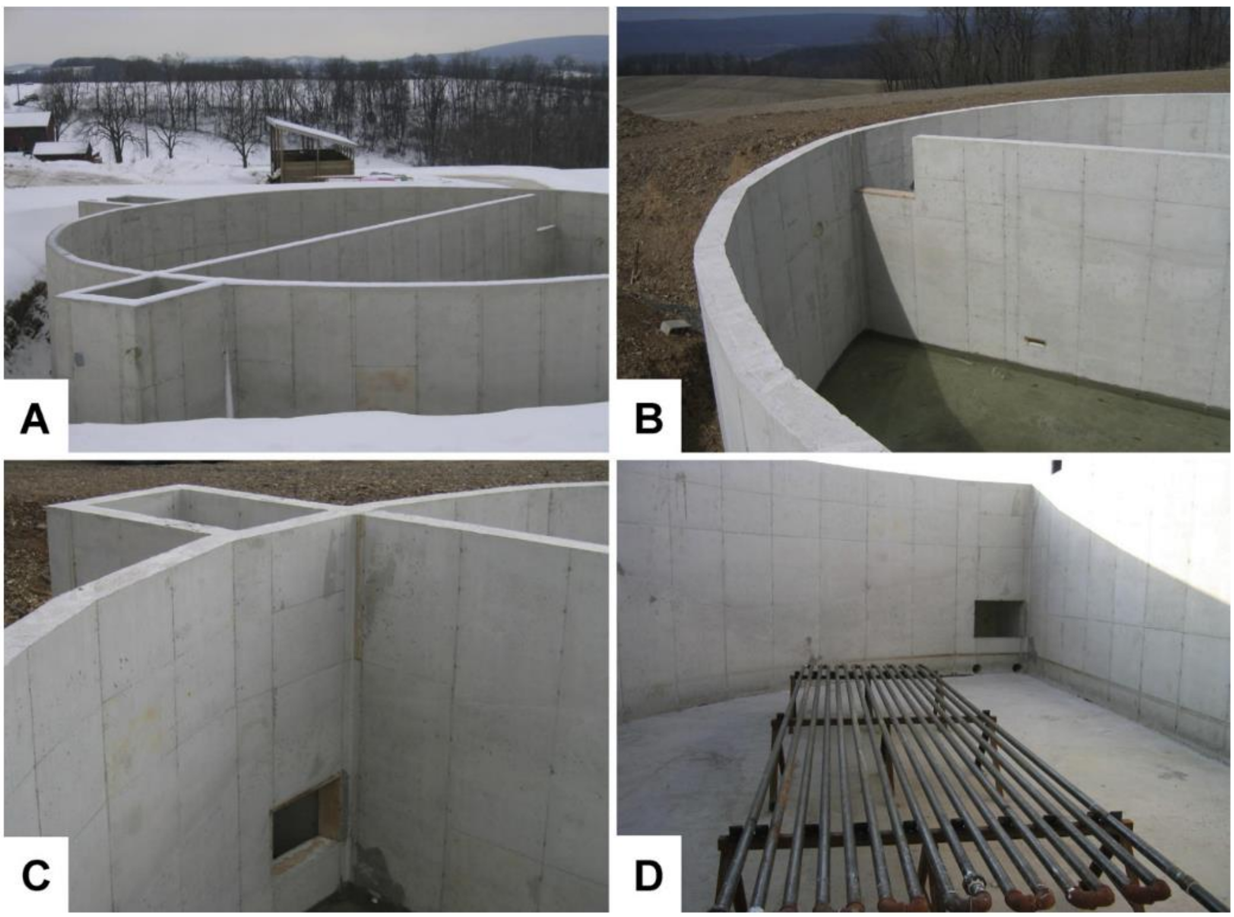

Figure A.1 Full-Scale Complete Mix AD (Meinin et al. 2014)

Figure A.2 shows two complete mix digesters that are no longer under construction. These two are on a dairy operation in California. The silver and green tank stores the biogas produced from both digester.

Figure A.2 Above Ground Complete Mix Digester

Figure A.3 is also a picture of a complete mix digester on a dairy operation, but this one is below ground. The smaller photo in the bottom left corner is where the biogas is stored for this digester.

Figure A.3 Below Ground Complete Mix Digester

Figure A.4 shows an example of a below ground plug flow digester on a dairy operation in Washington. The photo in the bottom left corner shows the biogas storage.

Figure A.4 Below Ground Mixed Plug Flow Digester

Figure A.5 shows the average government funding for ADs by state. This data is from the dataset I put together that was discussed in Chapter 2.

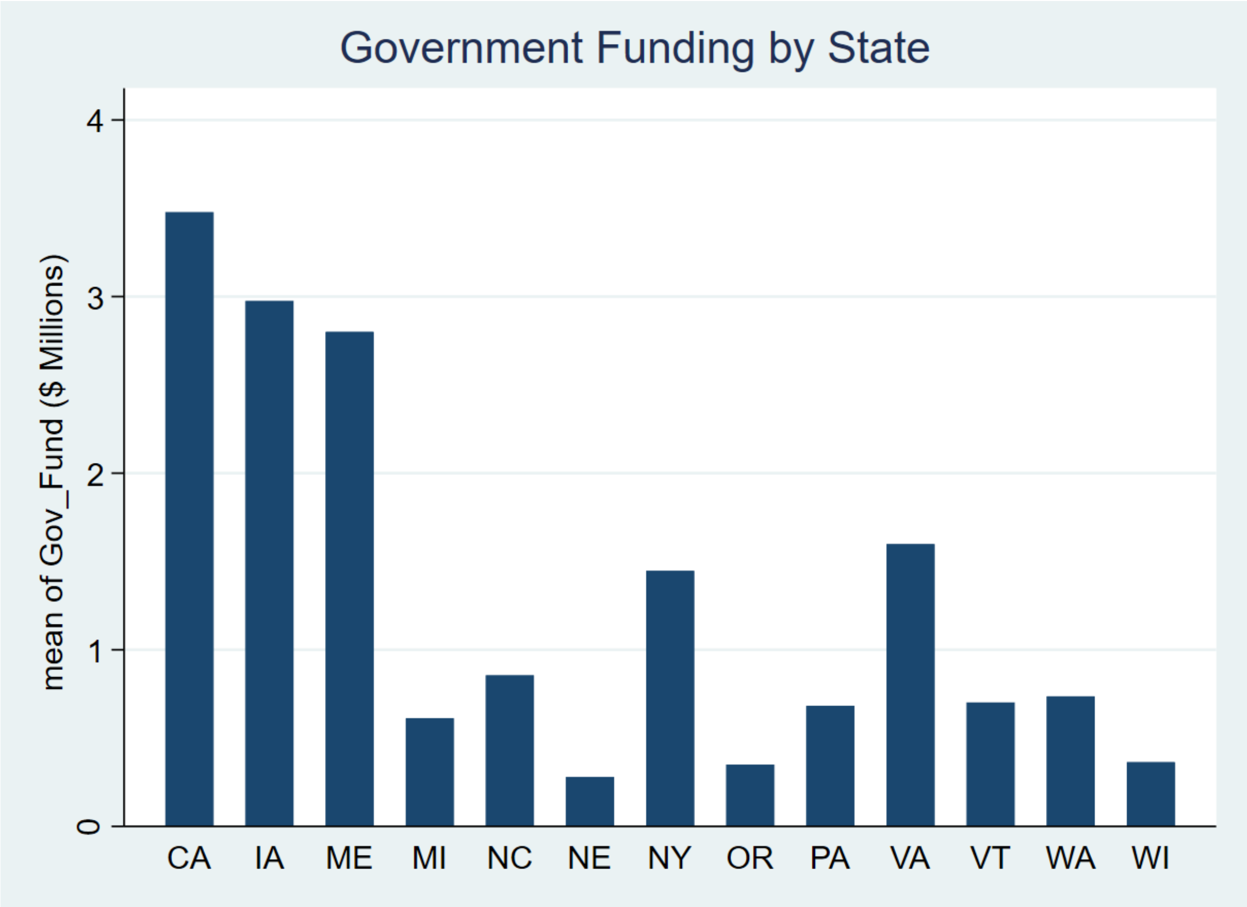

Figure A.5 Average Government Funding for Low Rate Digesters by State

Appendix B - Pictures of the AnMBR at Kansas State University

Figure B.1 Modified Steel Container

Figure B.2 Bioreactor Tank

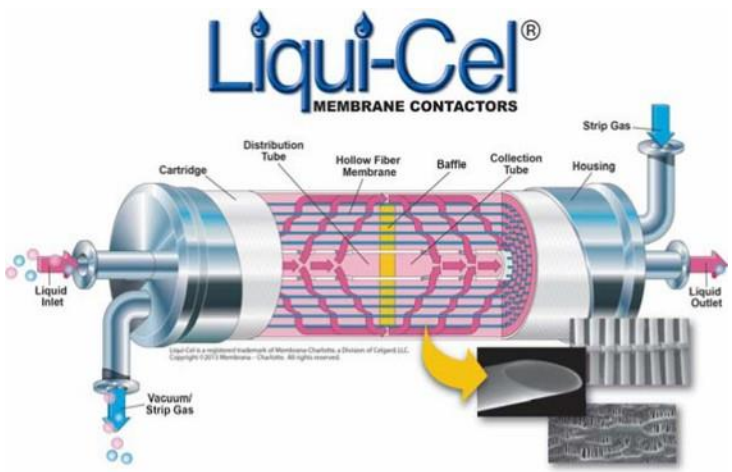

Figure B.3 Methane Membrane Contactor

Figure B.4 Coagulation-Flocculation-Sedimentation Process

Figure B.5 Ion-Exchange Column

Figure B.6 Chemical Cabinet

Figure B.7 Control Panel

Appendix C - Example NPV Calculation

Table C.1 represents the pilot-scale costs and revenue for the AnMBR+DM+P+N configuration over the first policy scenario considering permit trading only. The rows highlighted in gray were not used in the NPV of this specific scenario; however, as the configuration and policy scenario changed, the values used for the NPV also changed.

Table C.1 Example Pilot-Scale NPV Calculations

	Costs	Year 1	5; 15	10; 20
θd(Ω)	Farmer Share of Capital Costs	$ 467,843.00		
	Membrane Replacement (every 10 yrs)			$ 3,533.00
	CH4 Contactor Replacement (every 5 yrs)		$ 21,443.00	$ 21,443.00
e1	electricity w/ DM	$ 28.66	$ 28.66	$ 28.66
e2	electricity w/out DM	$ 28.00	$ 28.00	$ 28.00
β^{SOD}	Sodium Hypochlorite (Memb. Cleaning)	$ 53.20	$ 53.20	$ 53.20
B^{CIT}	Citric Acid (memb. Cleaning)	$ 354.01	$ 354.01	$ 354.01
B^{HYD}	Hydrochloric Acid (pH balance - P recovery)	$ 338.54	$ 338.54	$ 338.54
B^{LIM}	Quicklime (P recovery)	$ 42.56	$ 42.56	$ 42.56
β^{CLI}	Clinoptilolite (N recovery)	$ 974.00	$ 974.00	$ 974.00
	Total outflow	$ 1,790.97	$ 23,233.97	$ 26,766.97
	Revenue	**Year 1**	**5; 15**	**10; 20**
λ_1	Biogas w/ DM (sold at 52% of volume produced)	$ 28.92	$ 28.92	$ 28.92
λ_2	Biogas w/out DM (sold at 52% of volume produced)	$ 16.78	$ 16.78	$ 16.78
α	Recovered P	$ 18.82	$ 18.82	$ 18.82
δ	Recovered N	$ 476.85	$ 476.85	$ 476.85
ε_1	RINs w/DM (CNG)	$ 208.65	$ 208.65	$ 208.65
ε_2	RINs w/out DM (CNG)	$ 121.21	$ 121.21	$ 121.21
ϒ	Recovered Water (Quantity)	$ 2,555.00	$ 2,555.00	$ 2,555.00
μ	Water Quality Improvement	$ 47.64	$ 47.64	$ 47.64
π_1	Greenhouse Gas Mitigation w/DM, SCC=$42	$ 237.62	$ 237.62	$ 237.62
π_2	Greenhouse Gas Mitigation w/out DM, SCC=$42	$ 137.97	$ 137.97	$ 137.97
ϕ	Cost savings of an ODOR related lawsuit	$ 36,500.00	$ 36,500.00	$ 36,500.00
	Total Inflow	$ 3,288.24	$ 3,288.24	$ 3,288.24
	Total Cash Flow	$ 1,497.27	$ (19,945.73)	$ (23,478.73)
	NET PRESENT VALUE	**($497,374.41)**		

Table C.2 represents the pilot-scale farmer's share of capital costs for each configuration.

Table C.2 Pilot-Scale Capital Costs by Configuration

Configuration	Unsubsidized Capital Costs	Subsidized Capital Costs
AnMBR+DM+P+N	$ 467,843.00	$ 219,886.21
AnMBR+DM+P	$ 460,275.00	$ 216,329.25
AnMBR+DM+N	$ 436,333.00	$ 205,076.51
AnMBR+DM	$ 428,765.00	$ 201,519.55
AnMBR+N+P	$ 446,400.00	$ 209,808.00
AnMBR+P	$ 438,832.00	$ 206,251.04
AnMBR+N	$ 414,890.00	$ 194,998.30
AnMBR	$ 407,322.00	$ 191,441.34
BR	$ 403,799.00	$ 189,785.53

Table C.3 represents the full-scale costs and revenue for the AnMBR+DM+P+N configuration over the first policy scenario considering permit trading only. The rows highlighted in gray were not used in the NPV of this specific scenario; however, as the configuration and policy scenario changed, the values used for the NPV also changed.

Table C.3 Example Full-Scale NPV Calculations

	Costs	Year 1	5; 15	10; 20
θd(Ω)	Farmer Share of Capital Costs	$ 608,750.00		
	Membrane Replacement (every 10 yrs)			$ 18,672.00
	CH4 Contactor Replacement (every 5 yrs)		$ 113,648.00	$ 113,648.00
e1	electricity w/ DM	$ 180.38	$ 180.38	$ 180.38
e2	electricity w/out DM	$ 176.24	$ 176.24	$ 176.24
β^{SOD}	Sodium Hypochlorite (Memb. Cleaning)	$ 284.26	$ 284.26	$ 284.26
B^{CIT}	Citric Acid (memb. Cleaning)	$ 1,891.63	$ 1,891.63	$ 1,891.63
B^{HYD}	Hydrochloric Acid (pH balance - P recovery)	$ 1,808.94	$ 1,808.94	$ 1,808.94
B^{LIM}	Quicklime (P recovery)	$ 227.41	$ 227.41	$ 227.41
β^{CLI}	Clinoptilolite (N recovery)	$ 6,124.55	$ 6,124.55	$ 6,124.55
	Total outflow			

Revenue continued on next page…

	Revenue	Year 1	5; 15	10; 20
λ_1	Biogas w/ DM (sold at 52% of volume produced)	$ 154.56	$ 154.56	$ 154.56
λ_2	Biogas w/out DM (sold at 52% of volume produced)	$ 89.64	$ 89.64	$ 89.64
α	Recovered P	$ 100.54	$ 100.54	$ 100.54
δ	Recovered N	$ 3,000.99	$ 3,000.99	$ 3,000.99
ε_1	RINs w/DM (CNG)	$ 1,114.89	$ 1,114.89	$ 1,114.89
ε_2	RINs w/out DM (CNG)	$ 647.70	$ 647.70	$ 647.70
ϒ	Recovered Water (Quantity)	$ 13,653.47	$ 13,653.47	$ 13,653.47
μ	Water Quality Improvement	$ 1,488.72	$ 1,488.72	$ 1,488.72
π_1	Greenhouse Gas Mitigation w/DM, SCC=$42	$ 1,248.17	$ 1,248.17	$ 1,248.17
π_2	Greenhouse Gas Mitigation w/out DM, SCC=$42	$ 723.94	$ 723.94	$ 723.94
ф	Cost savings of an ODOR related lawsuit	$ 36,500.00	$ 36,500.00	$ 36,500.00
	Total Inflow	$ 18,024.45	$ 18,024.45	$ 18,024.45
	Total Cash Flow	$ 7,507.27	$ (106,140.73)	$ (124,812.73)
	NET PRESENT VALUE	($770,132.74)		

Table C.4 represents the full-scale farmer's share of capital costs for each configuration.

Table C.4 Full-Scale Capital Costs by Configuration

Configuration	Unsubsidized Capital Costs	Subsidized Capital Costs
AnMBR+DM+P+N	$ 608,750.00	$ 310,462.50
AnMBR+DM+P	$ 568,640.00	$ 290,006.40
AnMBR+DM+N	$ 441,747.00	$ 225,290.97
AnMBR+DM	$ 401,637.00	$ 204,834.87
AnMBR+N+P	$ 495,102.00	$ 252,502.02
AnMBR+P	$ 454,992.00	$ 232,045.92
AnMBR+N	$ 328,099.00	$ 167,330.49
AnMBR	$ 287,989.00	$ 146,874.39
BR	$ 269,317.00	$ 137,351.67

Table C.5 and C.6 represent the summary of capital costs, operating costs, private benefits, and social benefits associated with each configuration.

Table C.5 Configuration Summary Part 1

PART 1			AnMBR+DM+P+N	AnMBR+DM+P	AnMBR+DM+N	AnMBR+DM
Capital Costs d(Ω)	Bioreactor Tank		x	x	x	x
	Membrane Modules		x	x	x	x
	Ion-Exchange Process		x		x	
	CFS Process		x	x		
	Methane Contactor Process		x	x	x	x
	Bioprocess Tank Insulation		x	x	x	x
	Online Startup & Commission		x	x	x	x
	Remote Access Module Lease		x	x	x	x
Operating Costs	Electricity + DM	e1	x	x	x	x
	Electricity – DM	e2				
	Sodium Hypochlorite	B^SOD	x	x	x	x
	Citric Acid	B^CIT	x	x	x	x
	Hydrochloric Acid	B^HYD	x	x		
	Quicklime	B^LIM	x	x		
	Clinoptilolite	B^CLI	x		x	
Private Benefits	Biogas + DM	λ1	x	x	x	x
	Biogas – DM	λ2				
	Phosphorus	α	x	x		
	Nitrogen	δ	x		x	
	RIN-CNG + DM	ε1	x	x	x	x
	RIN-CNG - DM	ε2				
	Water Recovery (Quantity)	ϒ	x	x	x	x
Social Benefits	Water Quality Improvement	μ	x	x	x	x
	Odor Reduction	ϕ	x	x	x	x
	GHG Mitigation @ $42 SCC + DM	π1	x	x	x	x
	GHG Mitigation @ $42 SCC - DM	π2				

Table C.6 Configuration Summary Part 2

PART 2			AnMBR+N+P	AnMBR+P	AnMBR+N	AnMBR	BR
Capital Costs d(Ω)	Bioreactor Tank		x	x	x	x	x
	Membrane Modules		x	x	x	x	
	Ion-Exchange Process		x		x		
	CFS Process		x	x			
	Methane Contactor Process						
	Bioprocess Tank Insulation		x	x	x	x	x
	Online Startup & Commission		x	x	x	x	x
	Remote Access Module Lease		x	x	x	x	x
Operating Costs	Electricity + DM	e1					
	Electricity – DM	e2	x	x	x	x	x
	Sodium Hypochlorite	B^SOD	x	x	x	x	
	Citric Acid	B^CIT	x	x	x	x	
	Hydrochloric Acid	B^HYD	x	x			
	Quicklime	B^LIM	x	x			
	Clinoptilolite	B^CLI	x		x		
Private Benefits	Biogas + DM	λ1					
	Biogas – DM	λ2	x	x	x	x	x
	Phosphorus	α	x	x			
	Nitrogen	δ	x		x		
	RIN-CNG + DM	ε1					
	RIN-CNG - DM	ε2	x	x	x	x	x
	Water Recovery (Quantity)	ϒ	x	x	x	x	
Social Benefits	Water Quality Improvement	μ	x	x	x	x	
	Odor Reduction	ϕ	x	x	x	x	x
	GHG Mitigation @ $42 SCC + DM	π1					
	GHG Mitigation @ $42 SCC - DM	π2	x	x	x	x	x