THESIS

POST-OIL FARM-BASED ENERGY:

A PRODUCER'S PERSPECTIVE ON ANAEROBIC DIGESTION MANAGEMENT

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ABSTRACT

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The age of plentiful fossil fuels is reaching its end. This has and will continue to have significant impacts on many aspects of society, particularly agriculture. Renewable energy sources like biofuels provide one of many possible solutions for a transition away from fossil fuels. Anaerobic digestion (AD) is a renewable energy and nutrient management technology that produces biogas, a methane-based gaseous biofuel that can be made from organic wastes, like manure. As the AD industry in the US is relatively underdeveloped compared to the world, this research interviewed twenty dairy farm-based AD operators to uncover the realities of AD in the US, particularly the challenges faced, the solutions found, and the futures envisioned for the industry. Using a survey of both demographic, Likert and open-ended questions, twenty anaerobic digestion operators at grade A dairies were interviewed. After recording and transcribing, the interviews were analyzed quantitatively for discrete answers and qualitatively for themes in the operator's responses. The major themes found were challenges, knowledge, uniqueness, motivators, collaborations, and future. The challenges that arose were related to adoption, pre-digester management, peri-digester management, post-digester management, gas handling and utilities. The most significant motivators were environmental friendliness, zero waste, income incentives, power production, feedstocks, heat for water, automation, bedding, nutrient management, odor control, complementarity of enterprise, and digester friendly environments. The greatest areas of knowledge shared were about the learning process; digester systems; success factors; feeding and feedstocks; PPAs utilities, and RECs; gas and engine

management; digestate and bedding management; division of responsibility. Collaborations, unique enterprises, and discussions about the future were notably mentioned. This research demonstrated that AD is a management intensive renewable energy and nutrient management technology. There were three major management categories that arose from the research: 1) feedstock acquisition, and feeding management, 2) biogas and energy production management, and 3) effluent management. This research also showed that while AD technology is often commercialized as a renewable energy technology, the major benefit and challenge to managing these systems is primarily nutrient management. This would suggest that this technology is best conceptualized as a nutrient management technology with the side benefit of renewable energy. Additionally, this research illuminated the fact that while general management categories are the same, each AD system is unique in the solutions to its own challenges. Thus, learning how one's own system works optimally is an imperative to an AD operator's responsibility. That being said, mastering the management categories explored in this research can empower a farm operation to realize the greatest advantages, including generating revenue through tipping fees, and energy generation and crediting systems; displace costs for heat, electricity, bedding, mineral fertilizers; and improving one's nutrient recycling, crop productivity, and neighborly relations.

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DEDICATION

I dedicate this thesis to my family, present and future.

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CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 The importance of agriculture

The food we eat, the clothing we wear, and the multitudes of pharmaceuticals, chemicals, and materials on which we depend, come from agriculture. Agriculture is “the science, art, or practice of cultivating the soil, producing crops, and raising livestock and in varying degrees the preparation and marketing of the resulting products” (Merriam-Webster, 2019). It is the foundation of sustaining a civilization, both modern and ancient. Interestingly, the character of agriculture has changed in tandem with society; in other words the development of society has risen parallel to the development of agriculture.

In the progression of agriculture, three major ‘revolutions’ are considered. The first revolution, i.e. the Neolithic Revolution, corresponds with the societal transition from nomadic hunter-gatherer to settled farming practices occurring around 10,000 years ago in the Fertile Crescent, or the “The Cradle of Civilization”, in Mesopotamia, currently the Middle East (PCIFAP, 2008). At that time, the ancient Mesopotamians started domesticating plants and animals; the first animals, being goats, sheep, and then chickens (National Geographic, 2019).

The second revolution, i.e. the Industrial Revolution, occurred between the late 18th and early 19th century, primarily in Western Europe and the US. In this revolution, mechanization transformed practice; in its legacy the technologies of the reaper, thresher, combine, mechanical planters, cutters, huskers, cream separators, manure spreaders, potato planters, hay dryers, trains, trucks and tractors, refrigeration and milking technologies. Many of these technologies have been and are still critical to the success of the dairy industry.

The third revolution, i.e. the Green Revolution, occurred post-WWII to the late 1960's. The defining advances were in genetic selection, agricultural chemical use, irrigation and increasing mechanization.

As a result of these revolutions, our civilization has seen dramatic increases in agricultural productivity. Since the 18th century, at the beginning of the second revolution, it took 5 acres of farmland to feed one person; now just ½ an acre to do the same (Trewavas, 2002). Since the beginning of the third revolution, the yield of an acre of corn has increased nearly 2.5x, from 70-80 bushels/acre/year to now almost 200 bushels/acre/year (PCIFAP, 2008).

As a result of the advances made by these revolutions, food abundance created inexpensive feed and food for both animals and humans, respectively. Increasing concentration, specialization, and consolidation of the agriculture industry, (no exception being the livestock industry), followed with advanced nutrition, reproductive technologies, genetic selection, and overall better management allowed the agriculture industry to grow more food, with less space, and with less money. Consequently, since 1960, milk production has doubled, meat production tripled, and egg production quadrupled (Delgado, 2003).

Important to the revolutionary increases in productivity was the harnessing of energy, power, and chemical potential of fossil fuels like petroleum, coal, and natural gas. This fossil power fueled mechanization, specifically electrification, transportation, internal heating and cooling, and material manufacturing. Moreover, these technologies lightened and replaced the physical work of human and drought labor. Milking, hauling, irrigation, planting, harvesting, agricultural chemical application, processing, packaging, and trans-regional/national/global transportation: these once human and drought power activities were thoroughly transitioned to mechanization.

Mechanization for does *work*, which is measured in Joules (J), equal to the amount of *force* (f) applied over a certain distance (d), f*d=J. *Work* done over *time* (t) is called *power. Power* is measured in Watts (W); 1 watt equals 1 joule per second. One horsepower (hp) equals 745.7 watts. A 3.75 kW (about 5 hp) centrifugal pump can pump 1 centimeter-hectare 13 times faster than what the pre-modern driver of a pair of steers using a "self-emptying bucket into an irrigation trough" (Smil, 1987). Imagine the amount of power harnessed by modern milking machines, farm tractors, and irrigation systems. Include the amount of electrical appliances and lights. It's a tremendous feat of human power and energy-control.

Fueled by liquid, solid and gaseous fossil fuels--including petroleum, coal and natural gas--combustion engines and electromechanical generators harness and distribute power to mechanical technologies. These fossil resources are also used for manufacturing of agricultural chemicals and material production. Increased implementation of mechanization and use of agricultural chemical use has played a part in the near 30-fold increase in global fossil fuel consumption since the 1860's (Smil, 1987).

The following chapter will bring to light the finite and non-replenishable character of these fossil fuel resources, and the need for a transition towards renewability. This is the key to sustainability. Second generation biofuels may be one of many answers, including biogas from anaerobic digestion from dairy manures. To make positive change, the needed next agricultural revolution will have to act on an awareness of the interconnectedness of fossil fuel resources to agricultural production. Building that awareness is a goal for this research.

Overall, the following will explore and question agricultural sustainability. This quality, understood as the ability of our agricultural system to endure, to keep going, to continue, will be defined and rules will be set to understand what is more and less sustainable. Foundationally, sustainability entails 1) understanding the current status of reality and impending challenges, 2) anticipating both positive and negative impacts, and 3) preparing interventions to withstand and adapt to a necessary change. These three foundations will serve as the outline for the following chapter.

In this chapter (Chapter 1), a framework for agricultural sustainability is presented. Then, the current state of fossil energy, particularly that from petroleum, consumption is described, as well as potential impacts to sustainability. The discussion outlines biofuels as potential interventions to achieve fossil-energy independence, and why biogas from animal wastes, notably dairy manures, offers a promising solution. The technology and process of making biogas, anaerobic digestion, is illustrated with important parameters highlighted.

In Chapter 2, the conducted research is presented: A Producer's Perspective on Anaerobic Digestion Management. Using the voices of AD operators themselves, Chapter 2 outlines the challenges, the solutions found, and the future envisioned by those within the AD industry.

1.2 Assessing agricultural sustainability

"By failing to prepare, you are preparing to fail" - Benjamin Franklin

To strive for sustainability, as defined by the US Environmental Protection Agency (EPA) (2016), society must "create and maintain the conditions under which humans and nature can exist in productive harmony to support present and future generations." Alluded to above, there are three major categories of sustainability: social ("human"), environmental ("nature"), and economic ("productiv[ity]") (Purvis et al., 2018). Sustainability is the balance of positive and negative attributes, compared by absolute and relative weight, which makes discussions about sustainability convoluted and certainty difficult to achieve.

I argue for a simpler framework. In a resource-centric framework, sustainability can be simplified to resource inputs, outputs, abundance, depletion, and replenishment. This is reductive, and if something passes, it might need a secondary tri-categorical assessment. But if something raises concern in this assessment, there's reason to conclude a significant sustainability challenge.

Two measures for assessing agricultural sustainability are:

Measure 1) For outputs, like food, materials and power, to be continually produced, agricultural inputs that empower production must be maintained in both quality and quantity. For example, to plant a certain field to produce continually and at a constant rate, the same or similar quality and quantity of seeds, soil fertility, precipitation, sunlight, human/mechanical labor are required. Some of these resources can be recycled (e.g. water), some are depleted on use (e.g. sunlight, fuel, time), and some are transformed into a different state (e.g. seeds, fertilizer, solar energy). To maintain these resources, replenishment and/or procurement of alternatives is vital for continued production.

Measure 2) The production of outputs should not jeopardize the quantity and quality of inputs. This would be a negative feedback of production; for example, raising animals creates manures, and if manures and their nutrients runoff into bodies of freshwater or groundwater, contamination occurs, and the fresh water resource, which is needed to produce animals is spoiled. Thus, production jeopardizes its own productive needs.

Using these measures to assess the sustainability of fossil energy resources, which are in essence finite and non-replenishable, one starts to see this imminent challenge to agricultural sustainability.

1.3 Current state

1.3.1 The importance of energy resources

Around the world, but particularly in the US, the majority of the energy consumed comes from finite and non-replenishable resources, such as oil (petroleum), natural gas, and coal.
In 2017, the US consumed 16.5% (2234.9 million tonnes of oil equivalent (MTOE) = the energy released by burning one tonne of crude oil, equal to 7.33 barrels of oil or 310.8 gallons]) of total world energy consumption (13511.2 MTOE) (BP Statistical Review, 2018). Of the total energy consumed by the US in 2017, 84.2% was from finite and non-replenishable resources; 40.9% (913.3 MTOE) from oil, 28.4% (635.8 MTOE) from natural gas, and 14.9% (332.1 MTOE) from coal (BP Statistical Review, 2018). Furthermore, the US consumed 19.8% of 2017 total world oil energy (4621.9 MTOE), 20.2% of the total world natural gas energy (3156.0 MTOE), and 8.9% of total world coal energy (3731.5 MTOE). While the US is a major consumer in world fossil energy resources, it is also the top oil and natural gas producer, and the third biggest coal producer, behind China and India (EIA, 2018b; IEA, 2016) .

In the US, energy resource consumption is varied by sector and purpose (Figure 1.1), but primarily it is of fossil energy resources. According to the EIA (2018), 92% of the energy (705.6 MTOE) consumed by the 2017 US transportation sector was derived from oil. While 72% of the total oil energy went to transportation, 23% went to industry (EIA, 2018). Of the energy consumed by industry, oil contributes 38%, coal 5% and natural gas 45%. Of the natural gas consumed (705.59 MTOE), 35% went to industry, 28% to residential and commercial uses, and 34% to electric power. Electric power consumed 91% of the coal energy. In summary, much of the energy consumed by the US is from finite and non-replenishable energy resources.

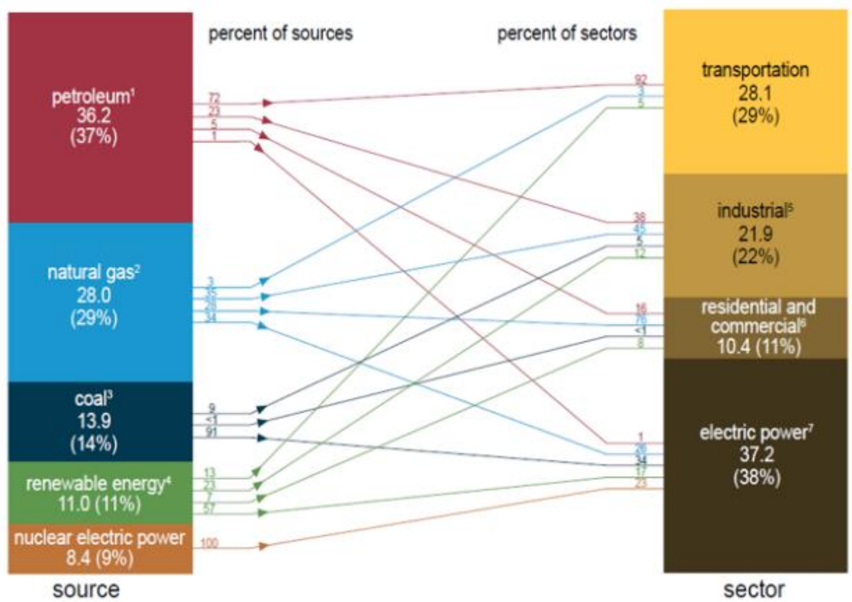

Figure 1.1: U.S. primary energy consumption by source and sector, 2017. Total = 97.7 quadrillion British thermal units (BTU) (EIA, 2018).

1.3.2 Energy inputs in agriculture

The US agricultural sector, composed of industry and transportation and reliant on electric power, also consumes vast amounts of finite and non-replenishable energy resources. In 2014, US agriculture consumed 43.2 MTOE of both direct and indirect energy, equivalent to the energy derived from burning 316.7 million barrels of oil a year; though this only accounts to 1.7% of the total US energy consumption, this is equivalent to the energy consumption of Columbia, the Czech Republic, or the Philippines (Hitaj and Suttles, 2016; BP Statistical Review, 2018). Of the energy consumed by agriculture, 29% was from producing fertilizers, 24% from diesel, 17% from electricity (of which 26% derived from natural gas and 34% from coal), 9% from producing pesticides, 9% from natural gas, and 12% other (likely consisting of 8% gasoline and 4% from liquified petroleum gas) (Miranowski, 2004; Hitaj and Suttles, 2016).

Specifically, agriculture consumes energy for manufacturing and application of agricultural inputs, processing, packaging, distributing/transporting, refrigeration, freezing, baking, preparation, canning, and disposal (Canning et al., 2010; Pimentel et al., 1973). Energy is consumed both “directly” and “indirectly” by US agriculture (Schnepf, 2004). Direct consumption includes the fueling of vehicles, machinery, and assorted farming equipment, and the use of electric energy (Pew, 2008; Schnepf, 2004). Indirect use includes the manufacturing of “fertilizers and chemicals [like pesticides] produced off-farm” (Schnepf, 2004). Specifically, nitrogenous fertilizers are derived from natural gas via the Haber-Bosch Process; phosphorus and potassium are mined, processed and transported by heavy machinery with fossil energy (Pew, 2008). Pesticides and plastics are also produced using petroleum-derived chemicals (Pew, 2008). According to Schnepf (2004), in 2003, total energy costs represented 14.4% of annual agricultural expenses ($198.9 billion). Fossil energy resources are integral to US agricultural production and for the US as a whole.

1.3.3 Finite and non-replenishable resources

By definition, finite and non-replenishable resources when consumed will eventually deplete. If these resources cannot be maintained in both quality and quantity (Measure 1), they pose a challenge for sustainability.

At the current rate of extraction, sooner than coal or natural gas, oil reserve depletion is predicted to occur on a global scale within the next 50 years. According to BP Statistical Review (2018), in 2017 the world contained 1696 billion barrels of proven oil reserves. A proven reserve is defined as “the volumes of crude oil which geological and engineering information indicate, beyond reasonable doubt, to be recoverable in the future from an oil reservoir under existing economic and operating conditions" (Hubbert, 1962). In 2017 the world consumed 4.6 billion tonnes of oil equivalent (BP Statistical Review, 2018), equal to the energy released by burning 33.9 billion barrels of oil per year. By dividing proven world oil reserves by world consumption, the world's proven oil reserves will be depleted in about 50 years. Unfortunately, much of the world is not continuing at the current rate of consumption; many areas of the world are increasing in fossil energy usage. According to Ridao et al. (2007), "energy consumption in developed countries grows at a rate of approximately 1% per year and that of developing countries at 5% per year". In accordance, total world consumption of oil increased in 2017 alone by 1.8%, (BP Statistical Review, 2018). World oil reserves are increasing extraction of this finite resource (BP Statistical Review, 2018).

In 2017, the US had about 50.0 billion barrels of oil in proven reserves (BP Statistical Review, 2018). In 2017, the US increased oil extraction by 5.6% to 13.1 million barrels per day, or 4.8 billion barrels per year (BP Statistical Review, 2018). At this rate, at the end of 2017 the US has 10.5 additional years of oil reserves in the ground. In 2017, the US increased consumption by 1.0% to 19.9 million barrels per day, or 7.3 billion barrels per year, the greatest amount since 2007 (BP Statistical Review, 2018).

If sustaining the levels of petroleum usage is going to be maintained, the US will need to import more oil resources. In 2017, the US increased importing oil by 0.2% to 10.1 million barrels of oil per day, or 3.7 billion barrels per year - which amounts to 14.9% of the total world imports. In 2017, the US increased exporting oil by 13.7% to 5.5 million barrels of oil per day or 2.0 billion barrels per year (BP Statistical Review, 2018). US consumption and exportation is increasing, reserves are decreasing, and consumption is increasingly heavily reliant on international trade.

It is important to note three aspects of depletion:

1) Depletion does not happen instantaneously. The extraction of oil resources from proven reserves, as M.K. Hubbard presented to the National Research Council in 1962, follows a bell-shaped (Gaussian) curve. When resources are found and plentiful, extraction rate accelerates. As the reserve is depleted, extraction rate decelerates and eventually, after a progression of time, dwindles and goes to zero. Somewhere between the beginning and end of total extraction, there is a maximum extraction rate: the peak of the bell shaped curve. The peak typically occurs after "roughly half of the recoverable oil in the field has been produced" (Hirsh et al., 2006). To compensate for reservoirs diminishing, "new reservoirs must be continually discovered and brought into production"; if new reserves are not discovered, world oil production cannot increase anymore (Hirsh et al., 2006). As total extraction is the culmination of many individual reserves, world total extraction similarly follows a Hubbard's shape curve. By most estimates, peak oil production will occur before 2040 (Hirsh et al., 2006; Schade and Pimentel, 2010).
2) As extraction of oil decelerates and the reserves of that resource dwindle, the capacity to extract that oil will decrease, and thus the final reserve remainders will become more energy expensive (energy returned on investment = EROI), and capital expensive to extract. In 1930, the EROI of oil was >100:1; in 1970 it was 30:1; and in 2005 it was between 11:1 and 18:1 (Murphy and Hall, 2010). As reserves dwindle, "the cost of obtaining fuels from domestic and foreign sources will rapidly increase" (Pimentel et al.,

1973). Before an energy or capital ROI of 1:1, one must decide when extraction is worth the cost and return.

a) The IEA (2008) predicts that by 2030 the price for a barrel of oil quadruples from $52.63 (Jan 17th, 2019) to $200. The likely future scenario will be that wealthier nations will have more capital to purchase and extract oil; and with more oil accessibility and consumption, as shown by Murphy and Hall (2010) and Kummel (1989), economic activity increases (in terms of GDP). This positive feedback allows for the greater purchase and/or extraction of more oil. As Hamilton (2009) stated "[national] income rather than price is the key determinant of the quantity [of oil] demanded". Additionally, the wealthier nations have greater oil efficiency and spend a smaller percentage of total GDP on energy, giving those nations advantage, a promising position for transitioning to alternative and/or energy efficient technology (Hirsh et al., 2006). For these reasons, the world's poor and developing countries are most vulnerable to inflating petroleum prices (Hirsh et al., 2006; Schade and Pimentel, 2010).

3) Peak extraction may be a more imminent concern than total depletion of fossil energy reserves. At peak extraction, if consumption of the non-replenishable resource is not voluntarily and preemptively abated to correspond with the diminishing amount available, there will be a critical divergence of resources available and resources required. Particularly, "oil peaking will create a severe liquid fuel problem for the transportation sector" (Hirsh et al. 2006). Following market tendencies, as petroleum becomes in short supply and great demand, it will increase the market price from "both domestic and foreign sources" (Hirsh et al., 2006; Pimentel et al., 1973).

1.4 Anticipating impacts

Oil (or petroleum) has three major uses:

1) Oil or petroleum is the "world's primary transportation fuel", like diesel, kerosene, LPG, gasoline and jet fuel, accounting for the fuel for about "90% of the world's transportation," and for 34.4% of world energy consumption in 2017 (Heinberg, 2006; BP Statistical Review, 2018). Of total US oil consumption, automobiles represent 25%, light trucks (vans, pickups, and SUV) account for 18%, heavy trucks (buses, on- and off-highway trucks) account for 16%, and 6% airplanes (Hirsh et al., 2006). A major reason why this fuel source has become so universal is that it can do a great deal of work at a relatively cheap price, all while being energetically dense and easily transportable. There is a lot of work (Joules) involved for a human to push a car up a 3-mile hill of 3% grade. If one was going to pay someone to push this car at the federal minimum wage of $7.25/hr, it would be much more costly than the gallon of gasoline in the tank minimally required to move the car. Imagine the incredible work done by combustion engines as vehicles, trucks, and tractors when planting, and harvesting 33 million tons of corn grain, as in 2007 (USDA, 2008). Then include the energy/work required in the transportation of that grain to a mill, then for distribution as feed and food ingredients to entities (like farms, peripheral and central food distribution and processing centers, and grocery stores) all over the country and the world. Many foods depend on multimodal, transnational and/or transcontinental transport. If one compares the work done by petroleum to the equivalent amount of work done by human or animal muscle, the sheer energetic/work done due to the combustion of petroleum is a great deal.

2) Oil is also used in the manufacturing of chemicals like "ethylene, propylene, and butadiene", which are used as derivatives, or platforms, for a variety of secondary chemicals, materials, and plastics (Heinberg, 2006). Some commonly known petrochemical products include disinfectants, detergents, dishwashing liquids, trash bags, plastic toys, anesthetics, antiseptics, aspirin, computer chips, tires, PVC water pipes, nylon, ink, eye-glasses, credit cards, and hearing aids (Heinberg, 2006). Of interest to agriculture, petroleum is used to make mineral, paraffinic, and petroleum oils, which are used as common pesticides (Bográn et al., 2006).
3) Oil, in a much less significant manner, is also used throughout the world for heating homes and electricity generation (Heinberg, 2006).

As oil fuels much of productive activities, there is a strong relationship ("nearly one for one") between energy consumption and "national and global economic production" (Murphy and Hall, 2010). Kummel (1989) found that "economic production was more dependent upon energy application than on capital or labor" (Murphy and Hall, 2010). Another correlation noted is that increases in oil prices "have preceded most US recessions since 1969" (Murphy and Hall, 2010; Hirsh et al., 2006).

To the agricultural sector, "unexpected changes in energy price or availability can substantially alter farm net revenues, particularly for major field crop production" (Schnepf, 2004).

> "In the short run, price- or supply-related disruptions to agriculture's energy supplies could result in unanticipated shifts in the production of major crop and livestock products, with subsequent effects on farm incomes and rural economies. In the long run, a sustained rise in energy prices may have serious consequences on energy-intensive

industries like agriculture by reducing profitability and driving resources away from the sector" (Schnepf, 2004).

Oil is a crucial element and fuel for our world, national and agricultural economy. Heinberg (2006) wrote that "oil represents the essence of modern life". If oil depletion occurs as predicted in the next 50 years, it will likely have "protracted economic hardship in the US and the world" (Hirsh et al., 2006).

1.4.1 Learning from the past

History provides a good illustration of the implications of peak oil and agriculture. In 2007-2008, petroleum price volatility increased, leading to a major spike in the price of petroleum. On the global agriculture sector, the price of wheat increased by 77% and rice increased by 16% in 2007; the price of rice increased an additional 141% in the first third of 2008 (Schade and Pimentel, 2010). This had dramatic consequences on food accessibility throughout the world. The president of the World Bank Robert Zoellick (2007-2012) stated that "rising grain prices pushed as many as a hundred million more people into poverty" (World Bank, 2008). This is an example of how world oil production and, subsequently, market price, can drastically impact poverty, hunger, and generally human suffering.

1.4.2 Climatic effects

Global climates are changing, primarily as a result of fossil fuels. About "98% of carbon emissions result from fossil fuel combustion" (Demirbas, 2006). According to the US Energy Information Administration (2018), combustion petroleum "accounts for 2.3 billion tonnes of carbon dioxide (CO_2)", or 46% of total CO_2 contribution by fossil fuels, as compared to "natural gas 1.4 billion tons [of CO_2] and coal 1.3 billion tonnes". According to Balat (2010), "CO_2 emissions from a gallon of gasoline are about 8 kg". Additionally, the emissions produced by gasoline-fueled cars accounts for "more than 70% of all carbon monoxide (CO) emissions, more than 40% of nitrogen oxide (NO_x) emissions, around 80% of all benzene (C_6H_6) emissions, 50% of atmospheric lead (Pb) emissions, 14% of all greenhouse gas (GHG) emissions and 19% of the CO_2 emissions" (Goldemberg, 2008).

The ability to trap heat is the most relevant aspect of greenhouse gases, like CO_2, NO_x, methane (CH_4), and primarily water (H_2O) vapor. When solar radiation reaches the earth, it reflects off the earth's surface as heat. As the heat makes its way into the atmosphere, greenhouse gases can absorb that heat energy, resulting in greater vibration between the molecules and increased heat retention and transmission. As these molecules are trapped within the earth's atmosphere, the heat stays surrounding the earth like a gaseous blanket. The more greenhouse gases, the greater the heating potential and thus the warmer the "blanket".

Of the total greenhouse gas emissions of 2016, CO_2 contributed 81%, CH_4 contributed 10%, NO_x contributed 6%, and fluorinated gases contributed 3% (EPA, 2018). While the relative abundance is significant, so is the relative heating potential of each gas, essentially indicating the severity of the gas in enabling the atmospheric greenhouse gas effect. The term global warming potential (GWP) is the term used to describe the relative heat capturing ability of a greenhouse gas compared with CO_2. CH_4 has a GWP of about 25, meaning that it is about 25 times more heat absorbent than CO_2 (EPA, 2018). NO_x has a GWP of 298 (EPA, 2018).

Due to the increasing quantity of most greenhouse gases, "average global temperatures are expected to rise 1.5 degrees centigrade by 2050 and then another 1.1-6.4 °C by 2100" (IPCC, 2007). This will affect precipitation patterns like floods, droughts, and macro-events like drying climates and soils, which will eventually alter regional climates (IPCC, 2007). Biological systems, including farmed agro-economic lands, will have to adapt to these changes (Schade and

Pimentel, 2010). As a result of the climatic changes, many predict world agricultural production will incur reductions, with estimates of 3.2% to 25%, which would result in amplifications of shortages/scarcities (Toop et al., 2017; Cline, 2007; Schade and Pimentel, 2010).

Climate and precipitation shifts are the result of a challenge to Measure 2 because the output of harnessed energy from fossil fuels directly impacts other needed agricultural inputs, namely agro-ecosystems, soils, and water availability. As challenges to Measure 1 and Measure 2 of the resource-centric sustainability assessment are apparent, there is reason to assume that these particular energy resources, notably petroleum, natural gas, and coal, are unsatisfactory in fulfilling society's needs for sustainable energy resources.

We need interventions to instill energy security and renewability.

1.5 Preparing Interventions

The era of fossil energy is predicted to come to a close and, yet, energy demand is growing (Vorpsi et al., 2011; IEA, 2008; BP Statistical Review, 2018). By 2050, given current rates of growth, the world population is expected to rise to 9 billion (Beddington, 2010). Standards of living are expected to rise as well, which equates to an increased resource-, especially energy-, consumption per capita (Beddington, 2010). According to the FAO (2009), to feed the additional people on earth by 2050, agricultural production will need to increase by 70%. This challenge will be amplified by the convergence of peak oil and a changing climate.

Three reasonable options can be considered for the future:

1) Produce or find energy analogs to fuel our current practices. In this scenario, the energy systems and technology stay the same, but their energy resource changes. Less preferred options are to use low EROI unconventional oils like heavy oils, oil sands and tar sands

(Hirsh et al., 2006). These are still finite and non-replenishable, yet their reserves are larger than conventional oil. A more preferred option is to use biodiesels from biomass, which have analogous chemical and energetic properties to petroleum-derived diesel. This may be the most convenient option, as no complete energy-system overall is needed to occur.

2) Modify or retrofit technology (i.e. fleets of vehicles, tractors, trucks) to consume other more plentiful or replenishable resources. In this scenario, systems and technology are changed to accommodate different energy resources. A less preferred option is investing in vehicles fueled on electricity manufactured from another finite and non-replenishable energy resource: coal. This being said, coal is more plentiful than petroleum so resource strain is less imminent (BP Statistical Review, 2018). Another option could be investing in natural gas and/or renewable natural gas (RNG = biomethane) fueled vehicles. This way natural gas would serve as a transition fuel until renewable natural gas becomes economically viable. An even more preferred option would be to transition a vehicle fleet to electric power produced from replenishable resources like solar, wind, tidal, and biomass. This may be the most expensive and safest option.

3) Reduce fossil energy consumption to match availability. This scenario preferably happens voluntarily with preemptive and gradual independence from fossil energy resources as reserves diminish. This might occur as radically improved energy conservation to a prescribed 2.6% decrease in fossil energy use per year, as suggested by Heinberg (2006). This scenario also can happen involuntarily if the world and especially the US continues on its path of fossil energy consumption without curbing consumption. The voluntary scenario is the most difficult option. The involuntary scenario may be the

least preferred and most hazardous as it would cause great economic, environmental and social impacts.

Preferably, all three voluntary options can exist concurrently.

1.5.1 Biofuels

As oil reserves become more limited, oil prices rise, and oil demand and the impacts from greenhouse gas emissions increase, the interest in biofuels as energy analogues increase worldwide (Balat, 2010). Biofuels are liquid fuels made from biomass, usually corn, sugarcane, and increasingly switchgrass, and are similar or analogous to fossil fuels.

There are four generations of biofuels.

1) First generation or conventional biofuels**.** These biofuels are made from food crop plants. Bioethanol, the most common biofuel and made from sugar cane, wheat, sugar beet and corn accounts for “more than 85% of the total biofuel usage” (Balat, 2010). As these fuels are derived from food crops, they compete for resources, including land, with food production; this negatively contributes to food security (Aro, 2016; West, 2013). According to the International Energy Agency (IEA) (2006), first-generation biofuel production accounts for “about 1% of all arable land and yields about 1% of global transportation fuels”. Cline (2007) theorizes that “⅓ of the world’s farmland may be devoted to ethanol production by 2050”. This scenario would create negative impacts on the ability of agriculture to produce food for feeding a growing population, as there would be less land devoted to human food, unless deforestation occurs to increase the arable land for agriculture. According to Schade and Pimentel (2010), “any substantial diversion of acreage from food to fuel will likely reverberate" throughout the world. The

world must consider carefully the impacts of producing first generation biofuels from food crops.

2) Second generation biofuels**.** These biofuels are made from lignocellulosic (plant dry matter) and non-food biomass, which is plentiful on earth. It can be produced with waste biomass, "straw, bagasse, forest residues, and purposefully grown energy crops on marginal lands" (Aro, 2016). Biogas, a second generation gaseous biofuel composed mostly of CH_4, can be produced from food and agricultural wastes, as well as municipal solid waste, industrial, and landfill wastes. More on this topic later.
3) Third generation biofuels. These biofuels are made with algal biomass on non-arable land, thereby implementable in concrete spaces, and within non-fresh water, thereby minimizing competition for fresh water (Aro, 2016).
4) Fourth generation biofuels**.** These biofuels are similar to third generation biofuels, except they utilize synthetic biology (Aro, 2016). This technology enlists genome identification and editing practices, including CRISPR (clustered regularly interspaced short palindromic repeats), ZFNs (zinc finger nucleases), and TALEN (transcription activator-like effector nucleases). These technologies can alter organismal metabolism, physical structure, nutrient profile, etc. For example, genome editing can increase algal metabolic production of oils, which could be potentially used for biodiesel. Alternatively, a photosynthetic autotroph, like an algae, could be genetically altered to exude large and profitable amounts of an industrially useful chemical, which could be captured for manufacturing high value products, like biomaterials and chemicals, pharmaceuticals and nutraceuticals. By not compromising the corporeal form of the living organism, products could be produced without destruction and replacement of algal productive units.

While all generations of biofuels are theoretically possible, the technologies for higher generations are less demonstrable on the commercial and industrial scale. As per the suggestion of West (2013), there should be gradual increases in investments and policy emphasis on second generation biofuel production from “grasslands and (non-food) waste products, rather than grains and oilseeds”. These resources could be used to create biomethane, a biofuel equivalent to compressed natural gas, and can be produced without further increasing competition with food production (West, 2013).

Biomethane is a derivative of biogas, the farm-based fuel of the future.

1.5.2 The farm-based fuel of the future: biogas

Biogas is a combustible gas composed of CH_4 (50-70%), CO_2 (25-45%), water vapor (1-5%), 0-4000 ppm of hydrogen sulfide, and 100 ppm ammonia (ETSAP, 2013; Klinkner, 2014; Smyth, 2013). It is primarily combusted for electricity and heat, and can also be liquified and compressed into renewable natural gas (RNG; i.e. biomethane).

Biogas is made through the biological process of anaerobic decomposition; in the industry referred to as anaerobic digestion (AD). Anaerobic decomposition is not new; it is a naturally occurring process mostly seen in “benthic deposits, hot springs, deep ocean trenches, rice paddies, and the intestinal tract of cattle, pigs, termites and humans” (Gerardi, 2003). The anaerobic digestion technology is not new either; human’s have been noted to use simpler forms of anaerobic digestion technology since the 10th century BCE (He, 2010; Bond and Templeton, 2011).

In the modern era, anaerobic digestion is an appropriated technology from municipal wastewater treatment plants to degrade organic solid wastes (Gerardi 2003). The first modern anaerobic digestion plant served the organic solids waste management needs of a leper colony in

Bombay, India in 1859 (Kangmin and Ho, 2006; Wellinger, 1999). By the late 19th century, anaerobic digestion technology became common in South China and in 1899 the first recognized US anaerobic digester was created: the Cameron Septic Tank (Gregory, 2010; AMS, 2017). In 1906, in Germany, Karl Imhoff patented the Imhoff tank, which was one of the first commercial scale digesters for treating wastewater, sourced from non-domestic and domestic wastewater streams i.e. sewage (Wellinger, 1999). In 1926, the Milwaukee Metropolitan Sewerage District was the first US commercial scale digestion plant for sewage (Kadish, 1928; MMSD, 2016). The first farm-based anaerobic digester was installed in Iowa in the 1970's (Davis, 2006). The history of anaerobic digestion is intimately connected to global and national technological development.

Adoption of this technology is varied. As of January 2018, there were 265 known livestock anaerobic digesters in the US (Nguyen, 2018). In comparison, China has about 8 million units, and Nepal has 50,000 (Nizami et al., 2013). The most anaerobic digesters in Europe are in Germany, with about 6,800. This is followed by Austria, Denmark, Finland, Sweden, Brazil (in South America), and then the UK (Nizami et al., 2013). Furthermore, Canada's legislature made provisions for anaerobic digestion as a major provider of their renewable energy target of 12% for 2025 (Nizami et al., 2013).

In comparison to global technological development, the US has been slow to adopt this technology. One hypothesis suggested is that energy prices affect public interest (Klinckner, 2014). During multiple periods including World War II, in the 1970's (particularly during the legislating of the Federal Water Pollution Control Act of 1972, or the "Clean Water Act" and, afterwards, the 1973 oil crisis), and the termed "Great Recession" in 2007-2008, there were limitations on the accessibility of fuel based on price and quantity. What resulted were renewed interest in and development of anaerobic digestion (Klinckner, 2014; Speece, 1983; Coombs, 1990). Between those times, when energy resources are cheap and available, interest wanes (Klickner, 2014).

This is a significant challenge for the anaerobic digestion industry: the dialogue of anaerobic digesters mainly concerns itself with energy production, overshadowing its other beneficial qualities. Anaerobic digestion does produce a combustible gaseous fuel that can create a stream of income via the energy sales, and credit programs. This, however, is rarely a significant income generator, at least, for dairy farmers. Notably, anaerobic digestion provides more than just an energy production method; these important services frequently elude the common dialogue.

Simply, anaerobic digestion catabolizes volatile solids (Gerardi, 2003). Most materials, i.e. feedstocks, put in the anaerobic digester have a liquid and solid content The total solids content of a feedstock is the proportion dry matter to total mass (including liquid or water content) within the feedstock. Of this dry matter, there are volatile and fixed solids. Also known as the organic solids, volatile solids are the dry matter that can be catabolized by chemicals or enzymes to simpler gaseous molecules like Ch_4, H_2, and CO_2. The volatile solids are what decompose to result in biogas and its intermediates in the anaerobic digester tank. Intriguingly, these volatile solids skip normal phase changes, going from the solid to the vapor phase, without liquifying beforehand. Fixed solids are the dry matter that stays in the solid phase through decomposition or changes to the liquid phase; these are found suspended in the liquid and solid portion of a feedstock. The ratio of volatile solids to the total mass of the feedstock is referred to as the organic fraction.

As the organic volatile solids of the feedstock break down, the capacity of the material to decompose, i.e. to putrefy, decreases (Gerardi, 2003). By using the natural bacterial process of anaerobic decomposition, the volatile solids are degraded to simpler organic compounds like "volatile acids, alcohols, methane, a variety of inorganic compounds such as CO_2 and H_2 gas" (Gerardi, 2003). Through a series of biological steps, some of these compounds can be captured for fuel, and higher value products. The fixed solids are often used as a soil amendment and fertilizer analogue.

There are a series of other benefits to anaerobic digestion. Anaerobic digestion decreases the solids content a feedstock, which makes it easier to pump out to fields compared to fresh and undigested manure; it balances and narrows the C:N ratio, and produces highly bioavailable ammonium nitrogen (Walker et al., 2009; Tambone et al., 2010; Moller, 2015). Biogas can be produced from organic wastes going to landfill, which account for over half of all municipal solid wastes (Klinckner, 2014; Amani et al. 2010); in other words, the costs of organic waste disposal and the space needed in the landfill could be reduced if organic waste streams were diverted to biogas production (Nizami et al., 2013). The methane released from organic wastes can be captured and used instead of releasing it into the atmosphere (NREL, 2013). The biogas can be used to displace fossil energy consumption from fertilizer production (ETSAP, 2013). The digested materials, i.e. the fixed solids, leaving the digester can provide farms with a green fertilizer analogue, alleviating some of the need for purchasing commercial N,P,K fertilizer purchases (West, 2013; AMS, 2017).

By increasing management of organic wastes, nutrient runoff from agricultural sites and municipalities can be reduced. With certain protocols (using high temperature and retention time), anaerobic digestion can inactivate viruses, bacteria, and parasites in feedstocks, principally manures, reducing public and animal health risks (ETSAP, 2013; Gerardi, 2003). It also reduces malodors from human-produced and animal wastes (Gerardi, 2003). By improving the management of nutrients, wastes and energy consumption, agricultural operations can become more intensive, especially as surrounding land and communities become more urbanized and less tolerant of odors (Klinckner, 2014). These advantages are harder to valuate than energy production in the current economic paradigm.

1.5.3 Potential for biogas

Biogas is made from organic wastes, which are plentiful and underutilized, especially in the US. The National Renewable Energy Laboratory (NREL) (2013) estimates the US could produce a potential of 7.9 million tonnes of CH_4 per year with biogas: 30% from wastewater, 31% from landfills, 24% from animal manures, and 15% organic wastes. This is equivalent to 431 trillion BTU's (british thermal units), or 10.8 million tonnes of oil equivalent (MTOE) (NREL, 2013). If plant matter, i.e. lignocellulosic biomass, was added nationally as a feedstock for biogas production, methane generation would increase to 4,318 trillion BTU, which is four times the equivalent energy derived from gasoline consumed in US (NPC, 2012; EIA, 2019). Liu et al. (2016) found that the US animal feeding operations alone "produce 1.3 billion wet tons of animal wastes per year". An average lactating dairy cow produces 80.0 lbs of manure a day per 1000 lbs animal unit (NRCS, 1995). A mature holstein dairy cow weighs about 1500 lbs or 1.5 animal units (Holstein Association USA, 2017). 94% (8.5 million) of the 9 million dairy cows in the US are Holsteins (Holstein Association USA, 2017). If we account only for mature holsteins (5.6 million, ⅓ being not mature), there are 8.46 million dairy animal units in US. If each dairy animal unit produces the manure that NRCS (1995) asserts, then the dairy industry produces 677 million lbs of manure a day, 247 billion lbs of manure a year, and 124 million tons of manure a year. This suggests a potential energy alternative to supply the energy needs of the country.

No matter the advantages and potential, the capacity for anaerobic digestion technology to prosper depends on its competitiveness with fossil energy and the price of carbon (Nizami et al., 2013). Fossil energy resource abundance and price are bound to change, and so may interest in anaerobic digestion.

1.6 Anaerobic digestion: the technology and process

Full installation of an anaerobic digester encompasses four different parts: 1) the production unit, which includes 3 components a) a holding/mixing tank for the inflowing feedstock, i.e. influent, b) a removal system for outflowing digested solids, i.e. effluent, and c) the digester tank itself; 2) the gas upgrading equipment including an H_2S "scrubber" or distillation system; 3) the gas storage facilities, much like an inflatable industrial sized bag; and 4) the equipment for energy capture, including the generator and the grid-connection circuitry (Wellinger, 1999).

1.6.1 Digester tank designs

There are many designs for anaerobic digesters. In the US, 42% of digester designs are plug flow, 37% complete mix and 14% covered lagoon (Sharvelle et al., 2012); these will be the primary ones discussed. Plug flow digesters are long, typically below-ground, heated, narrow tanks, in which solids traverse the digester as new feedstock is added (AMS, 2017). It can handle a total solids (TS) content of up to 11-17%, high enough to manage cattle manure, if managed well, even in arid climates (Sharvelle et al., 2012). As there is no mixing, nutrient and metabolic spatial stratification does occur, thus reducing its volatile solids catabolism and biogas potential (Sharvelle et al., 2012). However, there is less upfront, operational, and maintenance costs than a complete mix (Sharvelle et al., 2012).

Complete mix digesters are cylindrical, often dome-like, tanks that have internal mixing systems, which are usually a stirring paddle or a gas injection process (Sharvelle et al., 2012, AMS, 2017). The mechanized stirrers spread the variable nutrients evenly, create a more consistent methane production, dampen the chance for biological irritation from certain disruptive feedstocks, and have a more valuable effluent product than plug flow designs (Sharvelle et al., 2012). They can handle a TS of between 5-10% (Sharvelle et al., 2012). The major challenges with this design are the high capital costs and energy requirements for heating plus mixing the tank (Sharvelle et al., 2012).

A covered lagoon digester is a modern conventional manure storage lagoon with an installed impermeable cover that collects gas off the top (Sharvelle et al., 2012). It can handle a TS of less than 3% (1). This design is difficult to heat and thus to maintain optimal temperature for the biotic life inside, so it is only recommended in warmer climates (Sharvelle et al., 2012).

Beyond the scope of this research are also other digester designs: the Chinese dome, the Indian Gobar, an upflow sludge blanket system, and a fixed film system, among others.

1.6.2 Digester basic parameters

One of the most important parameters to ensure healthy biotic life in the digester is temperature. There are two major and one minor practice for temperature: mesophillic, thermophillic, and cryophillic. For the most common design, mesophillic, the digester tank is heated and/or maintained at 35 °C (100 °F) (Sharvelle et al., 2012). It retains the feedstock within the tank for between 20-30 days, i.e. the hydraulic retention time (HRT) (Sharvelle et al., 2012). It can handle more volume of feedstock, has less biotic health upsets, but also produces less biogas than thermophillic systems (Sharvelle et al., 2012).

In thermophillic designs, the digester is heated and maintained at 55°C (130 °F), usually needing the shortest HRT of 12-20 days (Sharvelle et al., 2012). These designs produce increased biogas per volume of feedstock in a shorter time, and have a greater pathogen destruction rate (Sharvelle et al., 2012). However, they also incur greater energy costs due to heat production and are more sensitive to disruptive feedstocks (Sharvelle et al., 2012).

Infrequently found on a commercial scale, cryophillic designs do not heat the digester tank, and should operate between 10-25 °C (14-77 °F) (Sharvelle et al., 2012, Wellinger, 1999). While these designs require little management and energy inputs, they have long retention time (50-150 days), produce little biogas, and are vulnerable to upsets (Sharvelle et al., 2012).

Hydraulic retention time (HRT) is the full period of time one cubic meter of feedstock material occupies the digester tank, equating to liquid volume of influent (m^3) divided by daily outflow (m^3 per day) (Klinckner, 2014; Wellinger, 1999). The HRT can depend on the design of the digester, the temperature, the health and composition of the biotic life inside, the material, and manager preferences (Klinckner, 2014). Increases in degradation rate lead to more bacterial growth, and lower HRT (Wellinger, 1999). Degradation rate of a feedstock material depends on its macromolecule composition; in order from least degradable to most: lignin, cellulose, hemicellulose, proteins, fats, and carbohydrates (Wellinger, 1999). For example, typically pig manure has a higher fat content than cattle manure with comparable cellulose and hemi-cellulose content, which results in pig manure having a lower HRT than cattle manure (Wellinger, 1999).

Organic loading rate (OLR) is the amount of organic (i.e. volatile solids) being fed to the digester daily, usually seen as a digester/managerial preference. Being a fraction of the total feedstock, the unit of measure is kilograms of volatile solids per square meter of feedstock per day (kg VS/m^3*d). As OLR increases, HRT decreases. Finding the optimal OLR for each feedstock for maximum volatile solid reduction and biogas production is important for digestion management. Of note, dairy cattle manure has a OLR of 2.5-3.5 kg VS/m^3*d; but dairy cattle manure with other co-digested feedstocks has an OLR of 5.0-7.0 kg VS/m^3*d. We can see from this that the dairy cattle manure with other co-digested feedstock has the largest ORL and thus more organic/volatile solids can be decomposed through the digester.

Chemical oxygen demand (COD) and biological oxygen demand (BOD) are measurements for indirectly determining the concentration of organic/volatile solids in a material and are indicators for OLR. Biochemical oxygen demand, measured in milligrams of oxygen consumed per liter of feedstock material (mg/l), describes the amount of oxygen needed to biologically decompose all the volatile solids in the particular feedstock (UGA, 2017). Chemical oxygen demand, a common alternative to BOD (UGA, 2017), measures the total amount of oxygen consumed by the water during decomposition. COD includes the oxygen consumed by non-microbial degradation/oxidation and microbial oxygen demand, while BOD only includes microbial oxygen demand.

Water content, the reciprocal to total solids content, is the ratio of the quantity of water to the quantity of dry matter in the feedstock. This is an important parameter when accepting and mixing feedstocks as different designs of digesters work best at different water contents. A digester operator may have to add water if feedstocks with a low water content or high total solids are accepted. This parameter also helps operators understand how much liquid will be added to the already filling lagoon. Water content also describes a fraction of feedstock that does not produce biogas.

Methane production potential is the ability of a feedstock material to decompose and produce methane. It is measured in cubic feet of methane produced per day per unit of feedstock.

This may be the most important reason for co-digestion, or mixing multiple different feedstocks together in the digester. Adding high methane yielding feedstocks to manure can have an additive effect on the methane potential and thus energy production (Braun and Wellinger, 2002). Finding this measurement and maintaining methane production potential at the known amount, can help to determine energy production per day (EPD) (kWh/day). The average conversion of feedstock to biogas (composed of CH_4, CO_2, $H_2O_{(vapor)}$, etc.) is 3.2 - 4.8 standard ft^3 of biogas per wet pound of feedstock (Klinckner, 2014), but this varies based on the feedstock. Two notes: for every 1000 lbs of a dairy cow, it produces 8lbs of volatile solids in manure per day, which amounts to 17 ft^3 of methane per day, and 4.7 kWh per day (Sharvelle et al., 2012, CAN WE ADD THIS ABOVE TOO). In addition, a "well insulated three bedroom home takes about 32 kWh or 110,000 BTU per day for heating during cold weather" (Sharvelle et al., 2012). Imagine the amount of homes, in addition to farms, that the dairy industry has the potential to heat and energize.

1.6.3 Feedstock analysis

All feedstocks are organic wastes. These can come from residences, municipalities, and industries like agriculture, in the form of sewer sludge, wastewater, human and animal manure, abattoir wastes, crops, and crop residues (ETSAP, 2013; Maralikrishna and Manickam, 2017). Examples of feedstocks include alcohol stillage from breweries and distilleries, dairy wastes from cheese/milk/ice cream/butter plants, potatoes, pulp and paper, seafood and shellfish, sugar, vegetables and fruits, grains and bakery wastes, corn and soybean residues, eggs, pectin, certain pharmaceuticals, and winery wastes (Gerardi, 2003). Generally, the organic fraction of municipal solid wastes (OSMSW) is a feedstock (Lukehurst et al., 2010). Depending on its concentration and the conditions of the digester, amenable chemicals to digestion include acetone, aldehydes, amino acids, glycerol, organic acids, phenols, glutamate, methanol, isopropanol, and isopropyl alcohol (Gerardi, 2003). A determinate of the ability to decompose, i.e the COD/BOD, is the length of the hydrocarbon/carbohydrates chains within the feedstock. Small chain carbohydrates, i.e. monosaccharides and disaccharides, such as glucose, fructose, sucrose, lactose, maltose, are easier to degrade than long chain hydrocarbons, i.e polysaccharides, such as cellulose, hemicellulose, and lignin, which specifically is impervious to anaerobic decomposition (Lukehurst et al., 2010).

Behind municipal, industrial, and agricultural wastes, manures are the most available source of feedstock (AMS, 2017). After feeding and digestion, animals excrete through their feces a portion of the micro- and macro-nutrients from their feed (Figure 2); Oenema and Tamminga (2005) found that 55-95% of the nitrogen in the feed is left-over in the feces and urine of a cow. What's left in the manure for anaerobic digestion depends on the diet and digestive system of the animal, which furthermore is affected by "species, sex, age, geographical and climatic conditions" (Lukehurst et al., 2010). These nutrients serve as the nutrition for the biological processes in the anaerobic digester and also what is left for spreading on the fields for fertilizing purposes. Table 1.1 shows nutrient content differences between different feedstocks.

Table 1.1: Feedstocks and their nutrient contents (Lukehurst et al., 2010)

Table 4 Examples of the nutrient content (kg/m^3 fresh weight) of some feedstock commonly used in co-digestion ([1]Institut fuer Energetik und Umwelt gGmbH, 2006; [2]Davis and Rudd, 1999; Kuhn *et al.*, 1995)

Feedstock	% TS	Total N	NH_4-N	Total P	Total K
Grass silage[1]	25 – 28	3.5 – 6.9	6.9 – 19.8	0.4 – 0.8	–
Maize silage[1]	20 – 35	1.1 – 2	0.15 – 0.3	0.2 – 0.3	4.2
Dairy waste[2]	3.7	1.0	0.1	0.4	0.2
Stomach content[2]	10.1	3.1	0.3	0.7	0.5
Blood[2]	10.9	11.7	1.0	0.4	0.6
Food leftovers[1]	9 – 18	0.8 – 3	2 – 4	0.7	NA*

Table 5 Approximate trace elements and heavy metals concentrations (mg kg^{-1} dry matter) in some feedstock types ([1]Institut fuer Energetik und Umwelt gGmbH, 2006; [2]Davis and Rudd, 1999)

Feedstock	Zn	Cu	Ni	Pb	Cr	Cd	Hg
Animals[1]							
Dairy slurry	176	51.0	5.5	4.79	5.13	0.20	
Pig slurry	403	364	7.8	<1.0	2.44	0/30	
Poultry (egg layers)	423	65.6	6.1	9.77	4.79	1.03	
Crops[1]							
Crops: Grass silage	38 – 53	8.1 – 9.5	2.1	3.0		0.2	
Maize silage	35 – 56	4.5 – 5.0	5.0	2.0	0.5	0.2	
Agri-food products[2]							
Dairy waste	3.7	1.4	<1.0	<1.0	<1.0	<0.25	<0.01
Stomach contents	4.1	1.2	<1.0	<1.0	<0.15	<0.25	<0.01
Blood	6.1	1.6	<1.0	<1.0	<1.0	<0.25	<0.01
Brewing wastes	3.8	3.7	<1.0	0.25	<1.0	<0.25	<0.01

Important to feedstock selection is proximity and affordability in terms of gas production, tipping fees and cost of management (Lukehurst et al., 2010)

1.6.4 Hazardous feedstock

In the exchange of feedstock, each party must understand the composition of the load. There are hazardous materials that can negatively affect human, animal, and environmental health, including the biology of the digester. These feedstocks include inhibitory contaminants (e.g. alkyl benzenes, phenols, alkanes, halogenated aliphatics, nitriles, amides and pyridines), chemical contaminants (e.g. antibiotics, disinfectants, anthelmintics, drug residues, pesticides, and heavy metals), biological contaminants (e.g. pathogens, prions, seeds, and spores), and physical contaminants (e.g. inorganics like rocks, plastic, sand, glass, low digestible materials (LCMs) (Chen et al., 2008 4; Al Seadi, 2001; AMS, 2017; Lukehurst et al., 2010).

Before feedstocks are digested, a pretreatment process usually occurs. While practices differ, this process usually includes blending different feedstock streams, removing undesirable particles, reducing bulky feedstocks, and buffering the variability of COD and BOD from the different feedstocks (Wellinger, 1999).

Some operators add chemicals like surfactants and absorbents to remove scum ("foaming") from the digested material; some add acids and bases to adjust pH, such as sodium hydroxide; and some don't add anything at all (Madamwar et al., 1992; Hobson and Wheatly, 1993, AMS, 2017).

1.7 Microbiology of anaerobic decomposition

Anaerobic digestion is technology that harnesses naturally occurring biological processes: the decomposition in an anaerobic, or oxygen-free, environment. This catabolism of feedstock is primarily controlled by bacterial activity (Gerardi, 2003)

There are three categories of oxygen-utilization in bacteria: 1) *strict aerobes* require oxygen to live, maintain health and reproduce, i.e. performances of normal cellular activity; 2) *facultative anaerobes* can perform normal cellular activities with or without oxygen; and 3) two sub-types of *anaerobes*, a) *oxygen tolerant* species that can survive in oxygen but not perform normal cellular activities, b) *oxygen intolerant* species, or *strict anaerobes*, that die in the presence of oxygen (Gerardi, 2003). In the feces of a single human or cow, at least 300 different species of bacteria can be found, most of which are strict anaerobes, and a majority of the remaining are facultative anaerobes (Gerardi, 2003).

Anaerobic digestion harnesses the metabolic potential of these anaerobes to create biogas in a four stage process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The mixing of the feedstock with water into a liquid slurry for injection into the digester starts the hydrolysis stage. In this phase, organic solids are solubilized in water, resulting in degradation, i.e.

hydrolyzation, of the feedstock polymers into more simple and bacterially accessible compounds (Gerardi, 2003). For example, with water, cellulose (a polysaccharide) hydrolyzes to more soluble sugars (disaccharides and monosaccharides); and proteins hydrolyzes to more soluble amino amino acids (Gerardi, 2003).

In the acidogenesis stage, fermentative (acidogenic) bacteria consume the simpler compounds from the hydrolysis stage to create propionic acid, butyric acid, formic acid, lactic acid, and some alcohols; in addition, acetic acid are produced CO_2, then consumed in the methanogenesis stage. This stage is facilitated by bacteria in the genera *Acetivibrio, Bacteroides, Bifidobacterium, Butyrivibrio, Clostridium, Enterobacteriaceae, Eubacteria, Lactobacillus, Peptostreptococcus, Propionibacterium, Ruminococcus, selanomas, and Streptococcus* (Archer and Kirsop, 1990).

The acetogenesis bacteria metabolize the volatile acids, and alcohols from the acidogenesis stage to create acetic acid or acetate, hydrogen gas and CO_2 (Gerardi, 2003; AMS 2017). This stage is facilitated by bacteria in the genera *Acetobacterium, Acetoanaerobium, Acetogenium, Butyribacterium, Clostridium, Eubacterium and Pelobacter* (Archer and Kirsop, 1990).

The methanogenic bacteria are the most sensitive to pH and oxygen (Gerardi, 2003; AMS, 2017). Metabolizing the acetate, acetic acid, CO_2 and the H_2, the methanogens produce CH_4 (methane) as one of the byproducts (Gerardi, 2003). This stage is facilitated by bacteria in the genera *Methanobacterium, Methanobrevibacter, Methanosarcina, Methanococcus, Methanogenium, Methanomicrobium, and Methanospirillum (*Archer and Kirsop, 1990).

To operate an anaerobic digester well one must provide favorable environments for the bacteria to facilitate the transition through the stages of methane digestion.

1.8 Energy generation from biogas

After methanogenesis takes place, the gas produced from the digestion, the biogas, becomes methane enriched. It is now ready for use. The next process after gas production is gas post-treatment, including desulfurization, upgrading, storage and utilization (ETSAP, 2013). The raw biogas, composed of primarily CH_4 and CO_2, can be used to produce energy without H_2S purification, i.e. desulfurization, but the 0-4000 ppm of H_2S hydrogen sulfide can be corrosive on engines and pose an odor nuisance problem (AMS, 2017). Farms use H_2S cleaners or “scrubbers” to purify the biogas of the H_2S. Using engine generators, i.e. a “gen-set”, electric power can be captured from the combustion of biogas, as well as co-generated heat, used for water and space heating (EPA, 2018). If the engine generator is running at full capacity and excess biogas is being produced, a flare can be used to ignite, i.e. oxidized, the CH_4 into CO_2, which lowers the greenhouse warming potential (GWP) of the gas leaving the facility. With an engine-generator, the biogas can be directly used as a fuel source for heaters, boilers, chillers, and dryers (EPA, 2018). It can also be upgraded, liquefied and compressed into biomethane, an analogue of compressed natural gas (CNG) that can be used for a natural gas pipeline injection and vehicle fuel for natural gas vehicles (NGV) (EPA, 2018). Iran has the biggest fleet of NGV in the world with 3.5 million, then China (3 million), then Pakistan (2.8 million) (NGV Journal, 2014). Italy has the largest NGV fleet in the European Union with approximately 823,000; Germany and Austria also utilize NGV and require 20:80 (biomethane to natural gas) fuel for their vehicles (NGV Journal, 2014; Nizami et al., 2013).

While all anaerobic digesters produce electricity, there are two major types of power purchase agreements (PPA), and two types of utility connections. In a net metering PPA, the engine-generator produces electricity, which first satisfies the on-site needs, and then any surplus is sent to the grid and exchanged for credits to be redeemed on an electric bill. In a "buy-all-sell-all" PPA, all electricity produced is sold to the grid, and all energy needed on-site is bought back at a lower wholesale price.

1.9 Digestate

After the four stage digestion of most of the volatile solids, leaving the digester is an effluent called digestate. (As a material, it is more stable, more nutrient dense, less odorous, more safe, with greater inactivated weed seeds (Sharvelle et al., 2012). Through digestion, the raw feedstocks increase in their nitrogen accessibility for crop utilization (Lukehurst et al., 2010); the amount of nitrogen accessible to crops in a given soil amendment is called the utilization percentage, a proxy of fertilizer value. Hansen et al. (2004) found that the volatile organic carbons that produce unpleasant odors, like isobutonic acid, butonic acid, isovaleric acid, and valeric acid, are reduced with anaerobic digestion (Lukehurst et al., 2010). Primarily with thermophillic anaerobic digestion, the EU recognizes digestate to have gone through pasteurization if the digester and digested solids are heated to 70 °C for one hour, then at 53 °C for a guaranteed retention of 5 hours (Lukehurst et al., 2010); in Germany, a pasteurization of 24 hours at 55 °C is allowable (Lukehurst et al., 2010). Using these processes or similar, operators can minimize the risk of manure and wastes of being a vector for human, animal and plant pathogens (AMS, 2017; Lukehurst et al., 2010).

The next step after the digester is most commonly a solids separator. The advantage of this step is for storage; the dry, fiber fraction can be piled and the liquid fraction can be pumped and stored in a manure lagoon for a more convenient time frame for field application (Lukehurst et al., 2010). There are many designs for extracting water out of digestate: belt press, sieve drum, screw press, sieve centrifuge, brushed screen, and decanter centrifuge (Lukehurst et al., 2010) The screw press has been found to have a high separation efficiency and reliability (Bauer et al., 2009).

Storage, usually in manure lagoons, should occur until times when plant uptake is the highest and rainfall is low, to minimize nutrient runoff and wasted time and energy (Lukehurst et al., 2010). Application times and rates should accord with crop nutrient needs (Lukehurst et al., 2010). The method for application is similar to applying raw slurry; in table 1.2, four conventional application techniques are described: trailing hose, trailing shoe, injection and splash plate. Wulf et al. (2002) found that applying digestate with a trailing shoe applicator with immediate soil incorporating had the least greenhouse gas emission of the different methods.

Table 1.2: A comparison of digestate application practices (Lukehurst et al., 2010)

Table 10. Example from Denmark summarising the characteristics of four digestate and raw slurry application methods (adapted from Birkmose, 2009)

	Trailing hose	Trailing shoe	Injection	Splash plate
Distribution of slurry	Even	Even	Even	Very uneven
Risk of ammonia volatilization	Medium	Low	Low or none	High
Risk of contamination of crop	Low	Low	Very low	High
Risk of wind drift	Minimal after application	Minimal after application	No risk	High
Risk of smell	Medium	Low	Very low	High
Spreading capacity	High	Low	Low	High
Working width	12–28 metres	6–12 metres	6–12 metres	6–10 metres
Mechanical damage of crop	None	None	High	None
Cost of application	Medium	Medium	High	Low
Amount of slurry visible	Some	Some	Very little	Most

The nutrient-rich digestate output can be used as a replacement for mineral (N, P, K) fertilizers. This would decrease fertilizer purchases, improve revenues, and enhance soil properties (ETSAP, 2013). Specifically, the solid portion often called the fiber portion of the digestate, has a high carbon content, making it suitable as a soil amendment or, upon drying, a construction or bedding material for animals (Liu et al., 2016). The liquid portion is rich in nitrogen and phosphorus, making it a quality liquid fertilizer (Liu et al., 2016).

1.10 Conclusion

The US has a significant amount of growth potential in this renewable energy technology. Given the sustainability concerns of decreasing availability and price of fossil energy resources, and the increasing impact of fossil energy utilization, scientific and technical advances in the field of biogas production with anaerobic digestion are making rapid advances. If successfully applied, these biofuels could provide replenishable, cleaner, large-scale alternatives to fossil fuels to ensure that agriculture endures.

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CHAPTER 2: A PRODUCER'S PERSPECTIVE ON AD MANAGEMENT

2.1 Introduction

Agriculture is the bedrock of society. The food we eat, the clothing we wear, and the multitudes of pharmaceuticals, chemicals and materials on which we depend, principally come from agriculture. Throughout its evolution, agriculture has increasingly relied on mechanization, electrification, transportation, internal heating and cooling, and material manufacturing. Evidence of this development can be seen with the technologies of milking, hauling, irrigation, planting, harvesting, agriculture chemical application, food processing, packaging and trans-regional/national transportation. These advancements are partially responsible for the great increases in agricultural productivity since the 1960's: a doubling of milk production, a tripling of meat production, and a quadrupling of egg production (Delgado, 2003).

Much of these agricultural technologies are energized by liquid, solid and gaseous fossil fuels, including petroleum, coal, and natural gas, respectively. In 2014, the US agricultural sector consumed 43.2 million tonnes of oil equivalent (MTOE) of energy, equal to about 316.7 million barrels of oil (Hitaj and Suttles, 2016). While this only accounts for 1.7% of total US energy consumption, it is equivalent to the total energy consumption of Columbia, the Czech Republic, or the Philippines (BP Statistical Review, 2018). Of the energy consumed by agriculture, 29% was from producing fertilizers, 24% from diesel, 17% from electricity (of which 26% derived from natural gas and 34% from coal), 9% from producing pesticides, 9% from natural gas, and 12% other (likely consisting of 8% gasoline and 4% from liquified petroleum gas) (Miranowski, 2004; Hitaj and Suttles, 2016).

The challenge with the use of fossil fuels is their limited future. Using data provided by British Petroleum (BP) Statistical Review of World Energy (2018), if current rates of extraction and consumption continue, with no new discoveries of reserves, petroleum has the shortest global and national time span, depleting in less than 50 and 10.5 years, respectively; then natural gas and, far later, coal. Due to these resources being integral to our activities, and their temporally short availability, we need to be adaptable to these changes to maintain food production.

Renewable energy offers a possible solution for fossil energy accessibility challenges. There are many types of renewable energy, e.g., solar, wind, hydroelectric, tidal, geothermal, nuclear, and fuels from biomass. One significant option, implementable on farms, is biogas, a methane-based gaseous fuel made from anaerobically decomposing municipal, industrial and agricultural organic solid wastes. The technology that can produce this renewable energy is called anaerobic digestion.

The process of anaerobic digestion is an advantageous nutrient management and renewable energy technology, especially for the livestock industry. The US livestock industry, including dairy, meat, eggs, etc., produces 1.3 billion wet tons of animal waste per year (Liu et al., 2016). Just the Holstein cattle alone in the dairy industry, which consist of the majority of dairy cattle, produce 124 million tons of manure a year (Holstein Association USA, 2017; NRCS, 1995). Using the volatile solids content of dairy cow manure to roughly extrapolate the biogas production potential, one can gain a perspective for the energy possibilities of biogas. For every animal unit (1,000 lbs), a dairy cow (averaging 1.4 animal units) produces 2,920 lbs of volatile solids per year, equating to 6,205 ft^3 of methane per year, and 1,715.5 kWh per year (Sharvelle et al. 2012). Considering that a “well insulated three bedroom home takes about 32 kWh per day [11,680 kWh per year] for heating during cold weather", and the 8.46 million animal units of mature Holsteins in the US, the potential for renewable energy production from anaerobic digestion could provide energy for over one million homes per year in the US (Sharvelle et al., 2012; Holstein Association USA, 2017).

Anaerobic digestion in the US is a small and novel industry, compared with elsewhere in the world. For comparison, China has about 8 million units, and Nepal has 50,000 (Nizami et al., 2013). The most anaerobic digesters in Europe are in Germany, with about 6,800. This is followed by Austria, Denmark, Finland, Sweden, Brazil (in South America), and then the UK (Nizami et al., 2013). Furthermore, Canada's legislature made provisions for anaerobic digestion as a major provider of their renewable energy target of 12% for 2025 (Nizami et al., 2013). According to Yao et al. (2020), global energy production from biogas in 2017 was 1,3331949 terajoules, a 57.8% increase from 2010. As of September 2020, according to EPA AGSTAR, there were 282 known livestock anaerobic digesters in the US, most around 10 years old (EPA, 2021). With this potential in mind, the following research explores the management of this technology in the US, particularly on dairy operations.

As the AD industry is a relatively undeveloped industry, there is both a great potential and challenge as it matures. To develop appropriately, it behooves the industry to listen and reflect on the voices of its members to understand what works, and what is not working. The goal of this study was to assess the current status of dairy farm-based anaerobic digestion adoption and management in the US, particularly in understanding its management. Knowing its status allows us to understand the current challenges, the initial reactions of the AD industry to overcome these challenges, and the possible areas of growth, especially in the realm of science, technology and policy. The researchers hypothesized that anaerobic digestion is a management intensive technology. If that is true, then there will be multiple management categories that are essential to its success. It is a goal of this research to outline the management categories, their challenges and the solutions that resulted. Next, the researchers hypothesized that each AD system will be run in foundationally similar, yet unique ways based on the environment and goals of the AD operator. If that is true, general themes will be able to be extracted as each operator will have essentially the same management challenges but have potentially different solutions based on their own unique circumstances. Using these hypotheses to guide the research, the management of AD will be illuminated and AD, conceptually, will be better understood in total.

As this research expressed the voices of those in the industry, it is likely to be most helpful for those in the dairy farm-based AD industry in the US. With this research and as the AD industry grows, we hope there is much to learn from the experience of its current operators.

2.2 Materials and Methods

2.2.1 Participant Recruitment

During the spring and summer of 2019, using the directory of farm-based anaerobic digester operations on AgStar (EPA, 2021), a convenience sample of dairy farm-based AD operations was surveyed. According to AgStar at the beginning of the research, there were 279 dairy farms in the US with operational anaerobic digestion technologies. The targeted population for this survey was the anaerobic digestion operators and/or owners at these farms. The selection criteria for participants included 1) consenting adult, 2) operator, technician, manager, or owner of an anaerobic digester at a US (grade A) dairy, and 3) recognized by AgStar as having a farm-based anaerobic digester.

Before reaching out to potential interviewees, the survey was submitted and approved for exemption by the IRB (#18-8325H).

A google search was conducted to find their contact information. Telephone calls were made to request survey participation. After confirming the correct identification, the request for participation was either provided in person or left as a voicemail to obtain participation. The request outlined who and from where the researchers were, and what the purpose of the survey was.

A follow up call to these individuals occurred approximately a week after the initial contact/voicemail, if applicable. Upon participant consent, the interview was recorded. One researcher served as the interviewer for all participants.

2.2.2 Survey Instrument Development

With the assistance of university faculty and industry professionals, a survey was developed that employed both closed and open-ended questions and those with a rating scale. This survey can be found in appendix A.

The survey contained six demographic questions about the farm, the digester technology, and management style. Questions included those related to the total number of dairy animals serviced by the AD, the type of housing provided to the animals, the type of digester tank, the number of employees or full-time equivalents, the number of years in operation, and the preceding waste management technique.

The survey included open ended qualitative questions that asked the participants about 1) the adoption period, including motivations for adoption, and challenges during that period, (as defined as the beginning of planning to one year into operation); 2) feedstock acquisition, tipping fees, challenges and subsequent solutions; 3) operation, biogas and energy production, and energy sale negotiation; 4) post-digestion material management; and 5) recommendations for policy and scientific advancement.

In addition, two rating scale questions were used. The first Likert scale question intended to ascertain the level of perceived difficulty for nine aspects of AD management: 1) daily operation and maintenance of AD machinery, 2) biology of anaerobic decomposition and biogas optimization, 3) training and managing personnel, 4) acquiring feedstocks and negotiations with feedstock suppliers, 5) using and selling energy from biogas and negotiations with utility companies, 6) using and selling digestate and negotiations with digestate buyers, 7) financing and utilizing federal, state, and private/local funding, 8) permitting and complying with regulation, 9) safety and hygiene while handling digestate. Participants were asked to select a number on a 1-to-5 scale, where 1 was least difficult and 5 was most difficult.

The second Likert-scale question intended to assess the level of agreement to the following statements: 1) AD integrated well into the farm, 2) AD improved energy independence, 3) AD improved the financial security of the operation, 4) AD improved the safety and hygiene of animal waste handling, 5) AD makes me a better neighbor, 6) AD has been a worthwhile investment. The participants were asked to indicate their level of agreement: agree, somewhat agree, neither agree nor disagree, somewhat disagree, and disagree. For both rating scale questions, AD operators could provide additional qualitative feedback with their responses.

To potentially equate management styles with capital injection into the AD project, total upfront cost, current annual operating costs and revenue, and projected return on investment were queried.

2.2.3 Data analysis

All surveys were recorded on an Olympus DS-40 Digital Voice Recorder (n=20). Upon uploading to a computer, the audio recordings were transcribed by the interviewer.

The transcribed interview was then divided into quantitative and qualitative responses. After training each reviewer, the team of three researchers, separated explicit answers and identified primary and overlying themes, which were thematically analyzed for frequency and quality.

To maintain confidentiality, all personal data associated with producers was coded and separated from survey responses. This code sheet was kept sealed and locked away and only accessible to research team members. Names were removed, leaving only generalized responses and the themes discussed. All identifying data will be destroyed after 3 years.

Data analysis consisted of two stages. During the first stage, two members of the research team independently read through the transcripts of the interviews to search for frequently mentioned themes. Reviewers independently identified themes and then sought concordance through discussion. Discrepant opinions were discussed until clarity and consensus were achieved. The finalized themes were identified and functionally defined. Exemplary excerpts were used to further clarify the theme, if necessary.

With these themes defined, the three-member research team reread the transcripts to highlight these themes. One third of the transcripts were coded and discussed by all three researchers to affirm standardization and intra-researcher reliability. The remaining two-thirds of the transcripts were assigned to be read by two researchers to determine consensus.

Upon completion of coding, excerpts were extracted and grouped based on theme. These grouped themes were further categorized into subthemes for further understanding of the complexity of the AD operator's experience.

2.3 Quantitative Results

2.3.1 Demographic data

Between January and August 2019, 250 calls were made to dairy farm-based AD operations within the US using the AgStar directory. Many calls did not lead to interviews due to the fact that many farms that had different ownership, no longer existed, and lack of response. Twenty dairy operators completed the survey. The surveys lasted between 17 and 74 minutes long with an average of 43 minutes (Table 2.1). The interviewees and their farm-based AD operations were from 9 states including CA, ID, MA, IN, NY, PA, OH, VT, WI.

Farm size by number of cows varied greatly, ranging from 200 to 16000 with a mean of 2560 (Table 2.1). Seventeen of the twenty of these farms provided free stall houses for their cows, however two had dry lot housing environments and one had a stanchion tie stall barn. Of the eight responders to the question of upfront costs of their anaerobic digestion system, the costs ranged from \$1.2 to \$21 million USD, with an average of \$7.8 million (Table 2.1).

The length of time the farms had their digesters varied from 1 year to 15 years, with a mean of 7 years (Table 2.1). The cumulative length of time was 157 years of experience. There are several different digester systems represented by the sample: eleven complete mix digesters, four plug flow digesters, two covered lagoons, one AD operator had two digesters that included one plug flow and one complete mix, a vertical plug flow system, and a custom build hybrid plug flow.

Table 2.1: Descriptive statistics on demographic answers from AD operators

	Mean	Median	Range	Standard Dev	n
Survey length (minutes)	43	40	17-74	14	20
Farm size (head of cattle)	2560	1730	200-16000	3460	20
Upfront costs ($)	7.8 million	6.5 million	1.2-21 million	5.7 million	8
Amount of time owning a digester (years)	7	8.3	1-15	3.7	20

Codigestion (defined as feeding organic substrates in addition to manure) was by far the most popular feedstock consumption style; four of the twenty used only manure. Of the sixteen remaining operations, four used onsite non-manure organic wastes including spoiled feed and feed refusals, and three were co-located on or co-owned a dairy processing facilities, ultimately using their high strength wastewater. Fourteen respondents used offsite organic wastes. These offsite wastes included food manufacturing wastes like dairy wastes (spent/purged ice cream, waste whey, yogurt, expired/poorly thermoregulated milk), cannery wastes, slaughterhouse and rendering wastes, bakery wastes, packaged food wastes (sodas, coffees, juices), and French fry oil and greases. Two digester operators conveyed that they were taking grocery store and restaurant wastes. Two digester operators were accepting wastes from biodiesel and ethanol plants.

2.3.2 Likert Scale Questions

Operators were asked about the difficulty of certain tasks involved in AD management on a scale ranging from 1 being very easy to 5 being very difficult. Please refer to Table 2.2 for complete statistics. From the responses, the following tasks are ranked from most challenging to least challenging: financing and utilizing federal state and/or private local funding (score: 3.2), permitting and complying with regulations (2.9), training and managing personnel (2.9), utilizing and selling biogas and negotiations with utility (2.5), biology of decomposition and biogas optimization (2.4), daily operation & maintenance (2.3), utilizing and selling digestate and negotiations with digestate buyers (1.8) (Table 2.2).

Table 2.2: Likert scale responses about the level of difficulty of certain AD management tasks. The response of 1 indicates being least difficult, and 5 being most difficult.

	mean	median	Standard Deviation	n
Daily operation & maintenance	2.3	2.0	1.0	17
Biology of decomposition and biogas optimization	2.4	2.0	1.3	16
Training and managing personnel	2.9	3.0	1.3	17
Utilizing and selling biogas and negotiations with utility	2.5	2.5	1.2	14
Utilizing and selling digestate and negotiations with digestate buyers	1.8	1.75	0.9	10
Financing and utilizing federal state and/or private local funding	3.2	3.0	1.0	13
Permitting and complying with regulations	2.9	2.5	1.3	16

The operators were then asked for their level of agreement to a series of statements. Their responses could be “agree”, “somewhat agree”, “neither agree nor disagree”, “somewhat disagree”, “disagree”. For a more complete description of their responses, refer to Figure 2.1. The statements in order of highest to lowest percentage of agreement were: “AD made me a better neighbor” (81.25%), “AD integrated well into the farming operation” (75%), “AD has been a worthwhile investment” (61.5%), “AD improved the financial security of the farm operation” (56.25%), “AD improved the energy independence of the operation” (50%), “AD improved the safety and handling of animals wastes” (50%). The statements in order of highest to lowest level of disagreement were: “AD improved the financial security of the farm operation” (18.75%), “AD improved the energy independence of the operation“ (12.5%), “AD has been a worthwhile investment” (7.7%), “AD improved the safety and handling of animals wastes” (6.125%), AD made me a better neighbor” (0%), “AD integrated well into the farming operation” (0%).

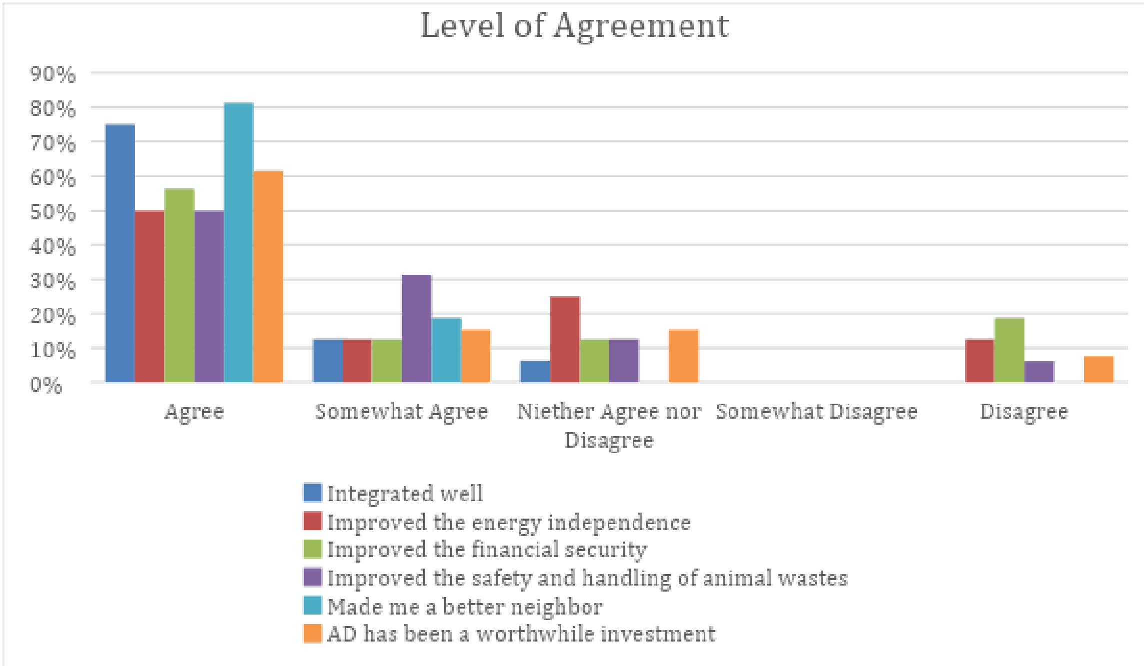

Figure 2.1: Bar graph showing level of agreement to several statements regarding AD ownership.

2.4 Thematic analysis

The finalized list of themes are as follows:

- Challenges - any part of the anaerobic digestion system or management of such a system that caused personal struggle by the anaerobic digester operator interviewed.
- Knowledge - the lessons learned through digestion management. Includes the process of learning, division of and gaps in knowledge, and how time is managed and prioritized towards AD among farm enterprises and tasks.
- Uniqueness - policy, geographic, economic, technological, etc. differences between AD operations that ultimately decide success or failure.
- Motivators - Positive intentions that instigated AD adoption, and benefits that were acquired by AD ownership

- Collaborations - the connections between third party and external players who were necessary to engage with for AD operations.
- Future - suggestions for and visions of the future by the AD operators.

These themes reflect important attributes of lived experience of anaerobic digestion management. Understanding these experiences should help to shed additional insights on this relatively novel industry in the US. In the following results section, excerpts from interviews are bookended with (I#), indicating the Interview number.

2.4.1 Challenges

Challenges were divided into 5 categories: 1) adoption period challenges, 2) pre-digester management challenges, including feedstock acquisition, 3) operational or peri-digestion management challenges, 4) post-digestion management challenges, and 5) gas handling, energy generation and monetization challenges. Of note, AD is an interconnected system, so while these challenges are described as separate, often they are explicitly or implicitly connected to other challenges. Thus, occasionally discretion was made to describe the challenge within one subtheme, though it could have been described in two or more.

2.4.1.1 Adoption challenges

The adoption period was defined as the moment planning started up to the first year of operation. Within this category, there were three major sub-themes of pioneering, permitting, and proximity, and a fourth minor subtheme: price.

2.4.1.1.1 Pioneering

The subtheme pioneering describes the experience of being the first to do anaerobic digestion, encompassing newness, and novelty in attempting to manage and succeed at AD. This experience was described by twelve of the twenty interviewees. This sense of pioneering was felt internally on farm, and externally off farm. Internally, there was a sense of lack of expertise:

> "Nobody on the farm knew the ins and outs of doing it. We just knew it was an operation that could be done. There was no expert on the farm." (I6)

This pertained to both the expertise of the workers on the farm and those who were contracted with completing the project:

> "A lot of the components were not necessarily new, but the people who did the construction, electrical, plumbing had never worked with anything like this before. So it was new for everybody." (I14)

Additionally, while experts experienced in AD were enlisted, there was even novelty in their aid:

> "We were the first [the AD design company] had in the US. So for them to come over here and develop a construction crew...they had to interact with a number of vendors that we had to help select. That was the biggest hurdle." (I12).

It must be noted that anaerobic digestion is not a self-contained entity; it is within a system of waste streams, regulations, and support services in order to make it work. Even more challenging, these external factors were often unpaved and required creative solutions for the success of AD. Utilities are necessary for making and selling electricity, however, in some cases the utilities were unaware of what to do with AD:

> “The problem we had is our utility...We were the first one to do anything like [AD]...They just didn’t know how to do it because they hadn’t done it before. We were pretty much at their mercy to do whatever they were willing to do.” (I14)

This extended to public policy regulators as well:

> “They initially had trouble getting a building permit for all this, because not too many people knew what AD actually was. So it took a lot of lecturing.” (I8)

One operator even mentioned that it felt like the regulators were “making up the regulations as we go” (I5). These excerpts support the statement that AD operators in the US may be “in uncharted territory” (I4) and “basically starting a new industry” (I7).

2.4.1.1.2 Permitting

To start an anaerobic digestion system at a farm, there are important permits that must be obtained and followed. These often vary by state and community. Permits and permitting challenges were mentioned by thirteen of the twenty interviewees. The following notes the types of permits mentioned and then the experience of getting the permits.

There were a variety of permits mentioned. The first group of permits related to waste handling and storage. In particular, the “manure pit” (i.e. storage or effluent lagoon or pond) needs to be permitted (I1, I19), to accept, handle, and ultimately spread organic wastes needs a permit (I7, I15, I17), and one dairy had to obtain a permit to certified themselves as a waste handling facility (I2). In addition, there were also air quality permits for the engine generators (I3, I8). And, finally, there were permits to produce energy called “certificates of public good” (I19). As these anaerobic digesters are on dairies, it must also be mentioned that permits for dairy concentrated animal feeding operations need also to be followed (I3).

Complying with various regulations was noted to be "quite a process" (I18). Some respondents were frustrated with the bureaucracy: permitting was a game of "trying to make all those people [in government] happy" (I9) and one will have to "deal with a bunch of government agencies that we're going to have to agree to disagree on" (I17). There was general frustration with the time and perseverance one needs to complete the permitting applications:

> "They really kinda put us through a ringer. They indicated to us through an email they were all set and they were going to issue us a permit and when we called about issuing a permit, they said they hadn't gotten around to issuing it yet. So it was frustrating." (I19)

Also mentioned was the challenge of keeping up the ever changing and stricter regulations:

> "That's a moving target that changes every year. Every year the legislative bodies are in session, you see more changes, more things to comply with, you got such a crowd of people looking over your shoulder to see what you're doing. It's actually getting hard to get your work done. So let's put a 5 [out of 5] on that also." (I18)

Said succinctly, "To deal with the government, sometimes they can be very challenging" (I17).

2.4.1.1.3 Proximity

Distance, both physically and conceptually, plays an important part in the management decision of AD. Fourteen of the twenty interviews mentioned proximity as a theme of challenge.

Proximity affects the infrastructure and the possibility of expansion of AD. To sell electricity to the power grid, there must be three-phase electrical infrastructure to hitch to, allowing for the possibility of dual flow from and towards the grid periphery. This can be expensive, especially with distances:

> "We had single phase power to the farm and if we wanted to produce electricity, we had to build 3.2 miles of three phase lines out to the sub-station. At our expense [for

$256,000]. Something that we'll never own and it was at our expense. That was for the privilege of producing power." (I18)

Additionally. noted several times, the proximity to natural gas injection stations, which potentially allow biomethane injection for household use, can affect the possibility of upgrading biogas for RNG instead of electricity. This distance leads some who are "not right next to a line" (I14) to have "no big incentives to do gas" (I4).

There is also an implication of proximity on feedstock acquisition. The closer feedstocks are the more accessible they are to the anaerobic digestion system. One operator described it as:

> "We're probably 15 minutes from the border so there's not a lot of big manufacturing plants around. You can import it from [other states], but we're not so interested in going to that extent. We use what's available to us." (I18)

Within the realm of feedstock acquisition, due to different economic and policy environments, state by state differences can lead to varied acquisition:

> "A problem that we've run into in the past is that there's a company that depackages relatively close to us. But dollars and cents-wise, it's cheaper for them to take it three hours one way and dump it in [another state] than it is to drive 45 minutes and bring it to us." (I17)

Proximity also relates to a growing trend of "our nationwide expansion of population and of urbanization" leading dairy farms to be "on the edge of populations" (I20). The closer neighbors are the more their interests matter and are vocalized to those with influence:

> "It's been a challenge...with the neighbors, meeting with the neighbors, and stuff like that. We live in the city. We live on a 400 acre farm in the middle of the city. We have a lot of neighbors." (I5)

While several operators mentioned that AD systems can lead to odor complaints, overall AD can help with odor issues:

> "Our farm is very close to a town. So if we're not doing things in the best possible way, we hear about it. Obviously the farm's gonna stink, because there's a lot of cows. But it could stink a lot worse if we weren't doing the things that we are." (I6)

Interestingly, several respondents mentioned a conceptual distance related to transparency, education, and misconception. To elaborate, the further the conceptual distance, the less transparency of farming operations, the more misconception about what is occurring on the farm. To lessen the conceptual distance, farmers discussed being open to educating and talking to their neighbors and politicians.

> "There's a huge lot of misconception about agriculture in the environment...and animal welfare...and if farmers don't take the time to talk and explain to people what's going on and how things are actually being done on a farm, most people are uneducated and they assume the worst….When we build our [AD] we had a township supervisor that didn't want us to build it because he thought it would be unsafe for the community. He also is a volunteer firefighter. And after we built our and got it up and running we had four local fire companies to take a farm tour. We invited them to the farm because here we have a flammable fuel that is constantly being produced and we wanted them to come see the farm so that at any point we had an emergency, they knew what they were coming to. And this township supervisor, after we gave them the farm tour, once the digester was up and running, came up and said "I'm sorry I didn't understand what you were trying to do. I'm sorry I fought against you"...It's something you gotta do...If you don't take the time

> to educate the public to some extent of what happens on a farm, it just gets harder to farm." (I16)

Another farmer described their challenge with lessening the conceptual distance:

> "The hardest thing is letting people know we even do this. From a public relations standpoint. I try to have open houses, try to talk to people about it. I talk to people on the street if they ask about it, I try to answer questions on the phone. I give tours. I would tell you that if you put in solar it takes up acres and acres and people see it. If you put up a wind turbine, people see it. My digester takes up about an acre and a half, and it's tucked behind the barn. People have no idea that on a daily basis I can create enough power to power 400 homes. Getting that message out is important...But it requires opening your doors, and farming isn't always pretty. I can't guarantee that when I walk out back that there isn't a dead calf, or born dead that hadn't been taken out to the pile yet. So those things happen and it's hard to get that out and it's hard to open your doors to the public, especially in a [liberal leaning state]. People read stuff on google, and they're sure that they know how to farm better than you." (I19)

Lessening the conceptual distance can be hard, but transparency and community engagement appears to be a way these operators improved the effectiveness of AD.

2.4.1.1.4 Price

A lesser frequently mentioned theme within the adoption period challenges was price or the financial aspects of adoption. Eight of the twenty highlighted that these projects are expensive. "One of the challenges is making it all pay…[as] digesters are very hard to cash flow" (I20). The major expense was noted to come from the building of the projects:

> “The expense of the actual physical construction of the components, but then the components themselves, the electrical components, the generator equipment, the expense is pretty high.” (I16)

Some operators mentioned finding grants (I15, I16), some were funded by federal and state agencies like the department of agriculture and the environmental protection agency (I17), some found partial funding from their utility (I18), and another had third party investors helping with the project initially (I20). There was mention that some of the state and federal incentive programs had “all dried up now” (I17), suggesting that “it was much easier five years ago” (I3).

2.4.1.2 Pre-digester management challenges

Pre-digester management challenges include issues surrounding feedstock and techniques on feeding the digester. There were four subthemes: acquisition of feedstocks and quantity control, volume/liquid management**,** quality control and feeding, and lastly sand contamination.

2.4.1.2.1 Acquisition and quantity control of feedstocks

The challenges related to acquisition and quantity control of feedstocks were mentioned in thirteen of twenty interviews. At the root of this subtheme is the fact stated here:

> “That’s one of the scary things. Once you get the digester all fired up and running and you cannot not have any food for it.” (I9)

Not all digesters accept external feedstocks. While those that do, the constant search creates a market of feedstock exchange that becomes a primary involvement of digester management. One AD operator described feedstock acquisition as:

> “A constant challenge; it doesn’t go away...What you have in a waste stream today could be gone tomorrow. You’re constantly looking for those streams.” (I7)

To further elaborate, one operator mentioned that when a “good” feedstock comes around, “you got to be on your game. You got to take it when they have it.” (I9). Another operator noted that, “when you have a good product, you want to secure it for as long as you can.” (I6).

To secure these streams, an important negotiation must take place: a feedstock contract. These contracts usually attempt to guarantee the tipping fee (i.e. the price paid for disposing of the feedstock), the quantity, quality, and consistency of delivery of the feedstock. One respondent explained that these contracts can include “up to a 45 page audits” of the materials exchanged (I4). In one state due to regulatory supervision of feedstocks, it can take a long time to secure and confirm a feedstock contract, creating additional time headaches (I4, I7). These contracts serve both the digester operator and feedstock supplier, and require upholding rapport and reputation. One operator mentioned cancelling a feedstock contract and “now that company’s got to get rid of all that stuff, it has to go somewhere else, and they’re freaking out” (I9). Maneuvering the feedstock market is dynamic and creating feedstock contracts can be time and energy intensive. Because of this, some respondents relied on third party brokers to provide this service (I6).

It is not entirely possible to guarantee the yearlong consistency of feedstock delivery with a feedstock contract: some feedstocks are seasonal. In one operator's case, they use glycerine bottoms, a biodiesel byproduct, which is diverted from the feedstock market to de-icer production in the winter. As a result, “it is a struggle in the winter to run on the other byproducts that we get that don’t help the gas production as much as the glycerine bottoms does” (I8). Another mentioned using ice-cream wastes from a local ice cream manufacturer that:

"likes to shut down for the [winter] holidays. They do some maintenance during that time. So you go maybe a month without that feedstock so now you're down on gas...There are times of the year when it's a bit of a challenge." (I18)

In some AD operations, especially the larger ones, maximizing feedstock acquisition is a priority. However, in some operations there are limitations to feedstock capacity. One operation failed to plan for the growth of the dairy, which resulted in sub-optimal capacity of the digester to handle even the on-site manure.

"If we had more capacity, our waste stream would be a more significant opportunity. Only if we had excess capacity. But we don't at this point...we have had to say no to everybody that calls" (I12)

One operation mentioned that due to their inability to combust the gas in their engine generator set at the rate produced, and their subsequent inability to store large quantities of biogas precombusted, they are forced to slow the biogas production and the amount fed to the digester and, subsequently, store the feedstock pre-digested. This has led to running out of storage space for the feedstock, and often "getting rid of a lot of [feedstock]" (I8). This created disappointment, making them wish "there was a way that we could store some of that gas. I'm sure there are bigger facilities than us that store that gas, but unfortunately we do not" (I8). Since they cannot, their method of production and source of income is constrained by storage space.

Additionally, which will be mentioned in more detail in the volume/liquid management subtheme, operators noted that one must consider the composition of the feedstock in relation to what can be stored and dispersed on the fields post-digester. One operator mentioned their feedstock selection process:

> "We'll check the nutrient content of it, of what the product is, what nutrients that it's bringing onto the farm because we need to farm the same land, and we don't want to bring in so many nutrients that we can't farm on the land. So we try to find products that are relatively low in nutrients, or that are not any more than what manure would have." (I13)

Feedstock acquisition is a balance between too much and too little, "feast or famine" (I4), but either way, there is a continual need to feed the digester.

2.4.1.2.2 Volume/liquid management

In seven of the twenty interviews, the subtheme of volume/liquid management was mentioned. This pertains to the need to balance the liquid volume brought into the digester with the liquid volume able to be stored and used. The basis of this balance is due to the fact that:

> "The digester doesn't change the volume of manure [or feedstock] that one has to deal with...So every gallon one brings into the farm to go through the digester, ends up in the manure storage. And one has to haul it back out." (I15)

The sources of liquid volume come from several sources. The most apparent source of liquid is through feedstocks, i.e. "high liquid substrate," (I3, I14, I19, I20), but also from misters that keep the cows cool in summer (I2, I16, I19), and from rain events (I16, I20).

As mentioned later, one notable challenge of liquid in feedstock beyond volume control is the effect of dilution on biogas potential of the feedstock. Methane is not directly produced from water and the digesters laden with water require excess energy to heat their internal contents (I16).

Volume of feedstock is retained throughout the digestion process. One's ability to handle the volume post digestion must be considered when accepting feedstocks pre-digestion.

2.4.1.2.3 Quality control and feeding

In thirteen of the twenty interviews, the subtheme of quality control and feeding was mentioned. One operator said it succinctly: "Acquiring good feedstocks is a challenge. Acquiring feedstocks has been relatively easy." (I9). Making sure what is being fed to the digester serves the health of the microbiota (i.e. "keeping the bacteria happy" (I16)) and maximizes the biogas potential are the ultimate goals of the digestion process. If the AD operator fails to do this, there is no money made and failure is imminent, as noted by one operator: "feed it right, and you won't have any problems. But once you start feeding the wrong stuff or too much of it, you're going to get sick...if you treat it right, it'll treat you right." (I12)

There were three challenging aspects of feeding management: quality, timing, and consistency. Some challenges the interviewed operators mentioned addressed quality control, including contamination with inorganic materials like plastics (I5, I6, I9, I13, I17), high lignocellulose content materials like sawdust and corn fodder (I17, I18), harsh industrial chemicals and animal health products (I10, I16, I17), and high strength feedstocks (I9, I11, I17). High strength is a term used to describe the Biological Oxygen Demand (BOD), as described by the USGS:

> "BOD represents the amount of oxygen consumed by bacteria and other microorganisms while they decompose organic matter under aerobic (oxygen present) conditions at a specified temperature." (USGS, 2021)

In terms relevant to an operator:

> "The higher the BOD the higher the biogas that it can produce. But you have to be careful about how much you dose your digester because it can get pretty excited and get

upset…[especially] if you put too much of that material without adequate buffering capacity" (I11)

Cranberry juice mix was described as having a high BOD and high potential for biological upset (I9). Some operators will test the product to make sure that it will serve the goals of biological health and biogas production (I9)

Timing and consistency seem to go hand in hand. One operator made the analogy:

"It's just like a cow. We want to feed the digester 365 days a year, and we want feedstock that comes in consistently and we can process a lot of volume if we're getting that volume day in and day out." (I13)

The problem with consistency is that often the feedstocks supplied are often irregular in quantity and quality as a result of feedstock suppliers generally needing "a sink for getting rid of product that people want…[making the digester often] being used as a dump" (I3). This inconsistency is usually unrelated to AD operators who only feed manures and onsite wastes to their digester, as these are relatively frequent and consistent. Externally acquired food wastes can create problems. One operator described their experience:

"We are getting grease trap [wastes]. One grease trap is heavy on grease and the next is heavy on water. Well we can't compare them and it's hard to get an accurate calculated number because it changes every load. So the plant is running mayonnaise this week, and mustard, but next week it's running ranch dressing and vinaigrette. Well, yes they are all high in calories but some have higher oils and some have higher energy levels compared to the other ones. And you're getting whatever they put in the tanker. Well, you can't say "hey guys, we have to run 50%, or 10% ranch...you can't dictate what you're getting".

This inconsistency can lead to irregularities in feeding and biogas potential, ultimately leading to a dynamic feeding management practice, one that is effort and attention intensive.

2.4.1.2.4 Sand contamination

The subtheme of sand contamination was mentioned in four of the twenty interviews. While less described, sand is a common bedding material in dairy systems and a corrosive contaminant to digester systems, thus relatively incompatible with AD. Sand, as an inorganic non-fermentable solid, will settle out in the digester, take up space, “clog pipes” and “weigh down the manure pit” (I13, I19). One operator mentioned how they installed a “sand lane” that lets the sand and heavy materials settle and be removed from the flushed dairy barn wastewater before reaching the digester (I3). The challenge with sand lanes is attempting to have the sand to settle out, but not the fermentable solids. This involves a “balancing game” of adjusting water flow rates through the sand lane, as one noted, “it’s pretty tricky” (I3). To exemplify the incompatibility of sand, one operator mentioned that their digester had gone dormant because the dairy operation changed from manure solids to sand bedding and had not installed yet a sand lane to prevent the settling of sand in the digester (I17)

2.4.1.3 Peri-digester management

Peri-digester management challenges involve issues surrounding the digester itself and when the organic contents are within the tank digesting. There were three major subthemes mentioned: the biology of digestion, mechanical issues, and staffing. One operator outlined peri-digester management well:

> “[AD] is a living organism. You gotta keep the bacteria happy, as well as all the mechanics and electrical components that don’t like to work all the time either. So you’ve got both a living object and a mechanical object and they gotta work together.” (I16)

2.4.1.3.1 Biology of digestion

As a subtheme, biology of digestion or “keeping the bacteria happy” (I16) was mentioned in seven of the twenty interviews. The major goal of the biological management of AD is “creating the best environment possible” for the bacteria (I3). As mentioned by one operator, “So long as your bugs are happy...your methane is usually very consistent” (I16). This involves managing a variety of parameters including “keep[ing] the bug fed all year long” (I2), mixing the feedstock thoroughly to incorporate the bacteria (I3, I9), optimizing the quantity and rate of feedstock input (I12), and the temperature within the digester tank (I2, I6, I13).

Temperature appears to be a significant challenge for some operators. Cold winter weather seems to create the largest hurdle. One operator described this as:

> “We’ve had trouble with heat exchange this winter not being able to keep it warm enough to make the bugs work to make enough gas to keep things running.” (I13)

Another operator mentioned a similar problem:

> “We had a two week spell, 10 days of below zero. And starting up a digester...it takes a tremendous amount of heat to do things and that was the biggest struggle to learn how to make everything function in that weather.” (I6)

Because these tanks are frequently exposed to external temperatures, winter weather plays a significant hindrance to keeping the bacteria ‘happy’. Internal issues also play a significant role. One operator mentioned an issue with solids accumulation on the inside of the digester:

> "We would take the waste heat from the engine and heat the digester with that, there's three pipes inside the digester to keep it warm. But that would build up with solids on it..., that's why we're not getting heat transfer anymore…So, we struggle maintaining temperature throughout the winter months... [the challenge is] it's a million gallon tank with a cover you can't remove without spending 1000 dollars. (I13)

Maintaining temperature involves buffering from the winter colds and also limiting internal hindrances to heat transfer.

The next parameter, "keeping bacteria happy inside a dark tank inside the ground" (I16) is quite a challenge. Some operators mentioned the indicators that they look for to assess the health of their bacterial population. One parameter is CO2 content of the biogas:

> "As long as your bugs are happy, your CO2 is pretty constant. It will go up if you have more manure solids than what the bugs will digest." (I16)

Another respondent mentioned bubbling or foaming:

> "When your bubbles are nice and big, and kinda have a rainbow color to them, your bacteria is happy. When your bubbles are really tiny and tight and look more like brown foam, then your bugs are not so happy. The real brown foam is you usually have too much sugar in it or you're agitating it too much and you're pissing the bugs off. And if you have no bubbles, that's not good. That means you're not doing [well]...your gas production has fallen way off, your bacteria are very sick and are not doing what they're supposed to. So the bubbles coming out of the digester indicate how well it's working" (I16)

In addition to indicating the health the bacteria, foam can directly affect the mechanics of the digester, as in the case of one operator where "foam screwed up our thermal couples and we overheated the digester." (I9)

2.4.1.3.2 Mechanical issues and maintenance

The subtheme of mechanical issues was mentioned in ten of the twenty interviews. From the interviews, regular maintenance must occur to prevent issues. This includes "changing the oil once a month [on the engine]" [I13, I16] and especially servicing the pumps to make sure they are not plugged and are flowing [I4, I13, I14). The latter issue is an outcome of what one operator mentioned succinctly:

> "Manure is not a friendly product...In wastewater treatment plants (WWTP), you got a lot more liquid there and they don't corrode or wear out, but you can have a WWTP on the edge of town and forty years later it still looks pretty decent. Take a manure digester and that amount of time, it looks like it's handled a lot of manure." (I20)

The innate characteristics of manure and other feedstocks and the volume passing through leads to a great deal of wear and tear on the pumps primarily, but also the mixers (if the digester design includes mixers) (I4, I13). There is also plumbing for the gas that needs maintenance (I13).

Another challenge acknowledged in the interviews was the unexpected and infrequent but serious mechanical issues of AD.

> "So the mechanical part really isn't that hard until something quits working and you gotta figure out what it is. You know you keep a list of spare components that most frequently go bad, which doesn't happen very often." (I16).

As mentioned, it can be electrical due to a "component failure or utility glitch that knocks us offline" (I16), but often "it's not usually the same piece of equipment" (I19). Fortunately, "when something mechanical breaks, you can usually find it. You can see it" (I16). It's important to check the mechanical features of the AD frequently because "if you fail to do that, you're inviting trouble. And if you fail to do that, you'll find yourself up to your chin" (I18).

2.4.1.3.3 Staffing and personnel

The subtheme of staffing and personnel challenges was mentioned in eight of the twenty interviews. Managing the biology and mechanics of AD is important. One operator described it as:

> "You have to have someone who pays attention to the details that keep it running because if it's not running you're not getting a return on investment. (I16)

The challenge that some operators find is that the attention needed to manage the AD can take away time and attention needed for handling the dairy and other daily operations.

> "It needs more time and management to keep the system running optimally. I used to do more of that myself but I'm running the whole farm and I don't get to spend as much time as I used to." (I13)

Due to the challenge of time management, hiring someone to specialize and attend to the AD seems to be how some operators have solved this challenge. But this solution comes with additional issues. Training is an issue:

> "I've struggled with that. I'm more of a hands-on person than I am a teacher...I can run it myself, but I've struggled with trying to manage someone else's time with it... It gets difficult to allocate time, and have someone on staff to utilize their time when there isn't a problem and have them available to work on it when there is a problem." (I13)

Finding the right employee for the position and retaining them is an issue.

> "This environment to work in is difficult, it stinks, it's manure, and you're on call 24 hours a day. So you have to find very dedicated individuals to do that. And it's hard to hire people like that." (I3)

Another operator further explained that:

> "If you can find a guy to show up, then you're doing good...no one wants to work and those who show up, those who want to work are old enough to be close to retirement." (I17)

In addition to hiring, some operators mention that they need, but lack, reliable third party technicians to turn to when there are serious issues (I15, I19)

Peri-digester management encompasses the time, energy and attention required to maintain the biological with the mechanical aspects of AD.

2.4.1.4 Post-digester management

The subtheme of post-digester management challenges was mentioned in fifteen of the twenty interviews. This operation of AD management involves the handling of the solid and liquid effluent leaving the digester. One operator reaffirmed the importance of this period:

> "The biggest challenge in [our state and others], really, is how to deal with the waste water stream after the digester." (I1)

Another further elaborated:

> "If there's one problem with the digester with bringing in the food wastes, there's a shit load of digestate to get rid of." (I4)

The interviews revealed three relatively distinct methods of usage, which may overlap and may occur concurrently: storage and distribution on fields, separation of solids for bedding, and selling the digestate.

2.4.1.4.1 Storage and distribution

The subtheme of storage and distribution was mentioned by eight of the twenty interviews. Storage is important as it relates to both the acceptance of feedstocks and manures, as well as distribution of effluent. One operator reported:

> "One of the problems with [certain feedstocks] is that most things include a lot of liquid that has to be handled. You're going to have to handle it somewhere." (I14)

The location where operators 'handle' volume is in a lagoon storage pond. The challenge with storage is that it is limited:

> "The digester doesn't change the volume of manure I have to deal with, so I still have 2.5 million gallons of manure storage that we are just almost outgrowing. So every gallon I bring into the farm to go through the digester, ends up in my manure storage." (I15)

One way to minimize the issues with storage is to separate the solids and liquids so that only liquids go into the storage vessel. When distributing onto fields, most operators spread the high liquid material. One challenge presented by a lagoon style digester operator, but may also be an issue with other styles of digesters, is solids accumulation ("sludge build-up" (I1)) within the storage vessel. The respondent reported that as much as one tries, before the digester or after, separation cannot get all the solids out of the effluent. This results in "residual solids" and "dead bacteria that collect on the bottom of the pond" (I1). If not handled, this can reduce the volume capacity of the storage vessel, thereby exacerbating storage challenges.

Distribution on fields is a common way of minimizing storage issues, but this method has additional challenges. The goal of field application is "try to apply [the digestate] at the right rate to get the maximum amount of nutrients" (I7). This also requires having "enough property" to spread all the effluent liquid, which one operator mentioned "relying on our neighbors to help there" (I4). The same operator mentioned the difficulty of field distribution "because of the sheer volume and the costs of doing it" (I4). In addition to volume and costs, distribution is affected by other factors including weather and rain:

> "The digestate is so water based...When you land apply it, you can only do it when it's dry out. If you do it when it's wet, it basically runs off like water...We're running into that situation that when you're spreading, the manure just runs down the hill. It doesn't sit where you spread it. You gotta put less on, more times." (I9)

One operator found a solution to this problem by:

> "Aerating everything on corn ground. We poke holes in the ground and then spread over the top of it. Nothing leaves the field in the current situation." (I4)

Another operator was exploring the technological options of filtering the separated liquid component to be injected into a nearby stream (I11). This would allow for lessened challenges with liquid volume handling. However, state regulations limited that behavior:

> "[The state] treats digestate and manure from a farm no matter what state it's in, whether it's filtered water or thickened manure, it's the same product. So the environmental regulations around that are pretty stringent... policy hasn't recognized technology yet. So the adoption of technologies ready to do that is going to be contingent on environmental policy catching up with the technology." (I11)

2.4.1.4.2 Separation and bedding

One option for the effluent post-digester is to separate it and use the composted solids for bedding. This subtheme, separation and bedding, was mentioned in seven of the twenty interviews. As one respondent noted, there is debate within the digester industry whether the costs of separators are worth the following challenges that arise from separating. One operator mentioned that separation may not be worth the costs because it is "an order of magnitude higher than our previous investment" (I11). Another operator mentioned reported to not separate the effluent because separators cost "$100,000 that we don't have at the moment" (I9). Of course, "separators are not cheap" but the return occurs when selling the solids and displacing the costs of bedding and the costs of liquid fertilizer (I12). A challenge with the separators themselves that one operator mentioned was struvite buildup on the roller presses:

> "We do have a problem with struvite, it's a calcium buildup. That gets built up in the digester, mainly the effluent, it gets built up in the roller press and stuff like that. It's like brick hard when it forms...when that stuff gets on those mixers, even those mixers are running, it builds up on the posts that the mixers get on and it just gets like cement." (I8)

When the separators are down, this can lead to bedding shortages:

> "The press has some problems every so often, so it is a big deal if that is down for a day or two, because then they don't have bedding or very little bedding for the cows...That can be a problem, because if it was down for a week then they'd have to go somewhere else for their bedding...It'd be additional cost, in addition to the cost to fix the press." (I8)

When using digested solids for bedding for the cows, "[it] takes more management to make sure it's properly composted" (I15). If time and attention are not adequately allotted towards the curing of the digested solids, udder health issues can arise. Two operators mentioned how the digester would digest the solids too much; in one case it would digest the solids into too fine a material that made it "harder to maintain udder health for [their] cattle" (I13) and the other did not have enough solids to bed their cattle (I17). Both operators ended up switching back to sand bedding in an attempt to lessen their bedding challenges. One mentioned that these bedding challenges were not problems with the digested solids themselves, but was instead a problem of "the guys at the farm weren't doing their jobs" of solids/bedding management (I17).

2.4.1.4.3 *Selling the digestate*

The subtheme of the marketing and sale of digestate was mentioned in seven of the twenty interviews. The promise of finding a market for the digestate may be dependent on the issues related to nutrient loading in concentrated areas:

> "We have 550,000 head of dairy cattle right here...We have a very concentrated number of cows. We are starting to get over nutrients especially in phosphate, and we need to get that out of here." (I3)

This might require separating "as much nutrient [from the liquid], not so much the nitrogen, but the phosphorus and potassium out of the material' (I3) and "reduce the volume and get rid of some of the water, and ship it that way" (I4). By changing it to a form that is shippable, "you could get it to other parts of the country to use it for fertilizer" (I3). One respondent summarized the problem as:

> "That market is saturated and there are warehouses with quite a few bags in them...So it's not a business model that's sustainable...Get over bagging the manure fibers. It is not the way to pay for your system. Period." (I20)

In other situations, the market may be unsaturated, but it's inconsistent and unreliable (I14). One respondent suggested creating a nutrient management and valuation plan with neighbors that attempts to “get the value of the nutrients on your neighbors land and to have a neighbor that understands the value of those nutrients” (I20). One operator had found success in finding value for their digestate by registering their solids as a certified fertilizer, thereby differentiating it and expanding the market (I7).

Making sure one has a plan for the effluent post-digester is important for the success of AD management.

2.4.1.5 Gas handling, utility issues, and policy and monetization strategies

This final subtheme in challenges was mentioned in all twenty of the interviews. The fact that biogas is a valuable and an important product of AD, it requires particular attention and comes with its inherent problems.

2.4.1.5.1 Gas Handling

As a subtheme, gas handling was mentioned in twelve of the twenty interviews. The major topic covered was hydrogen sulfide (H_2S) gas cleaning. As one operator put it: “H_2S is one of the evils of the anaerobic digester” (I12). Another operator described the problem broadly: “Long term viability of the mechanical equipment is significantly impacted by H_2S” (I10). Another respondent added, “H_2S is very corrosive on all your components including your engine” (I16) and “the sparkplugs” (I8). Many operators invest in gas cleaning or ‘scrubbing’ which is another biological system that uses bacteria that filter and absorb from the gas and excrete the sulfur in a mineralized form (I13). This system has its own challenges, as explained by one operator:

> “We have a scrubber for cleaning the gas, which is another biological system, which needs to be maintained to keep the H_2S low going into the engine. That’s another system

that needs a lot of maintenance and time and money...[The bacteria in the scrubber] excrete the elemental sulfur, which plugs things up if you don't stay on top of it. I didn't stay on top of it, and everything's plugged up now...It'd be nice to get an easier way to get the H_2S out of the gas so that we do not have engine troubles." (I13)

This is exacerbated by a problem that the same operator had when the scrubber manufacturer went bankrupt, resulting in not getting "the support to keep this system running to the level that it should be at" (I13)

Some operators proactively noticed the challenges of the system and decided that the cost of the system was not worth the benefits of inhibiting engine corrosion. One operator described the price they paid:

> "We held out to see what was going to work and what wasn't before we spent a quarter of a million dollars...The piece was $125,000 and then you have to pay for delivery, and then you have to rent a crane, I have to pay the guys to set it up. It was probably closer to $200,000. It was expensive." (I20)

Another operator described their process of deciding whether or not to purchase one, which ultimately they decided not to:

> "No we actually do not [have a scrubber]. We attempted to and we couldn't get things working. As we researched things, people I knew who were doing it quit doing it because it was too expensive to maintain the units. So they thought it didn't pay to do it...the engine people claim that we need to change the oil more frequently and the gas is a bit more corrosive. They figure the maintenance cost is probably higher, but I'm not sure you can justify spending too much money to bring those numbers down." (I14)

Finding ways to reduce the H_2S without a scrubber requires additional research and may be a future technological advancement. One operator actually used a pretreatment to the feedstock to reduce H_2S. They explained:

> "We actually have to treat one of the products, it's a dietary supplement byproduct, it's high in sulfur. So every time we get a truckload of that, we treat it with ferrous chloride to neutralize it. We dump about 900 gallons per truck load of that dietary supplement that we get in. so when the H_2S ...when I see a spike in that, I usually dump a couple 100 more gallons than the normal just to try to help neutralize the H_2S." (I8)

Another aspect of gas handling relates to the gas storage, particularly when there are power outages. As the engine generator sets are connected to the grid, when the power goes out, gas consumption through the engine halts, leading to buildup that needs release. In most cases: "When the generator is down, it goes out the flare. If it isn't, it goes through the generator" (I10). However, in some cases the flare is an electric component that requires functional grid ties. One operator did the following to bypass this issue:

> "We've made so much gas that we'd have trouble getting rid of the gas out to the flare, when the power went out. So we put in a gravity flare for $30-40,000, so when the power went out we could still get rid of the gas without having it go into the atmosphere." (I13)

The last gas handling challenge mentioned was the shear danger of the methane rich flammable biogas:

> "The gas, you gotta be on your toes, you breathe that in and you die. You just got to know what you're doing. I have been doing it for 9-12 months and I have already burned my eyebrows off. Things can happen. You can only learn some of those lessons once." (I9)

2.4.1.5.2 Utility issues

As a subtheme of challenges, utility issues were mentioned in thirteen of the twenty interviews. Utility companies are the gateway to monetization through power purchase agreements, which are affected by the policy environment. The division between utility issues and policy and monetization strategies is complicated. To simplify the difference, utility issues pertain to the operators' experience of the utility, which is noted in this excerpt "[the people at the utility company] are not helpful to deal with normally" (I14). Utility issues often may involve the experiences of money. Monetization strategies involve the payment plans between the operators of AD and the utility companies, as described here:

> "We had a problem with getting paid, we were on a variable rate, the power at the time was paying 12 cents and then it dropped to 7 cents, then guess what? You can't pay for that with that type of return." (I18)

With these functional definitions, one may start to see the challenges that arise through the gateway of the utility company. Frustration was common in the interviews when discussing utility company challenges. It seemed to arise from the power utility companies have in deciding the financial success of AD and the mercy the AD operators are to utility companies' decisions. This can be heightened by the novelty of AD:

> "I don't know how helpful they were. They're not helpful to deal with normally. The problem we had is our utility: we were the first one to do anything like that. They had very little experience with solar panels or anything similar at all. Even though the neighboring utilities had several online for a year or so, they were unwilling to talk to them to see how they handled it. They just didn't know how to do it because they hadn't

done it before. we were pretty much at their mercy to do whatever they were willing to do." (I14)

Another operator elaborated:

- "The dairy is powered by a [utility] co-op, they do not have to offer net metering...they can do whatever they decide. In other words, if we're producing electricity in the middle of the night and there is no demand, they say "well you're not going to get much of anything, if anything at all". Electric companies actually have a monopoly if they want to admit it or not." (I17)

Several operators noted frustration, in addition to the power of the utilities, but also the reluctance of the utilities to invest in green energy:

"Utilities are very independent, very self-serving, and they don't care about green energy. They just care about making money." (I12)

One operator further added that, "The power companies really don't care to buy [digester produced] electricity much" because they prefer to not "have to deal with a multitude of owners/operators, like you would have with a digester system" (I20). This can lead to relatively ineffective negotiations:

"They set the price and tell you how they're going to credit it. I didn't have a choice: take it or leave it….The negotiations are not something that really can be done." (I10)

One operator describes their negotiation process for getting a permit for power production:

"The utility company is pretty ugly, in my opinion. They ended up charging us $400,000 for a permit. And then they walked away. We have to sell the power, we have to make the power purchase agreement, we have to do this and that. So I'm kinda strong armed...That's kinda a cynical view, but I just had to pay $400,000 to a power company

> for them to even look at me. And it's taken...that was in September and it's March and we still haven't got hooked up. It's just whatever they felt like charging us. I can't answer it any better than that. They're claiming its upgrades to their system, but I think it's just fixing their antiquated system and they can be paid for it. Like I said, I have a cynical view and a biased opinion. But that's what I see" (I9)

This permit seemed to relate to what another operator described as an interconnection fee:

> "One of the other challenges is interconnection fees. So to connect to the power grid, power companies sometimes have to update their wiring. Well they want the final user to pay for that. Even though our farm was updated to put in that last 200 ft of wire, two power poles was $38,000. The competitive bid was $8,000. So they made an extra $30,000 bucks before we ever turned on the switch. I've heard of instances of over $1,000,000 proposed fee for an interconnection." (I20)

Another respondent offered a similar experience:

> "[Utility name] is our provider here and they're obligated to take the power, they're not obligated to pay you nothing for it. But they're big enough to tell you to shit in your hat or they say, 'we need to upgrade X,Y,Z and it's going to cost $1.2 million and you're going to like it'...It has been challenging for us to deal with them. In turn, we pay the price which I would honestly tell you, it's probably not as fair as it could be. And they don't have to be fair." (I4)

Ineffective negotiation with utilities is a significant problem:

> "You've got to make money from the methane gas and if you don't have utilities that are either interested in buying electricity or you don't have a mechanism for selling the renewable natural gas, if you don't have those mechanisms, what are you going to do

with the methane? You're just going to flare it? You're not going to make any money out of it." (I7)

Additional hurdles were expressed in that even when the AD system is functionally tied to the grid after utility negotiations, there still were problems with connectivity.

"Sometimes our utility will knock us offline if there are fluctuations in the utility. It'll knock us off line and shut things down, so it's not always a component failure but a utility failure that'll cause us problems...because we are tied to the grid all the time." (I16)

This can create losses in energy production, delivery to the utility, and consumption on-farm (I8).

2.4.1.5.3 Policy and monetization

As a subtheme, policy and monetization was mentioned in thirteen of the twenty interviews. This subtheme revolves around costs of the AD, as described below, and the ways of payment that can happen:

"I think one of the biggest problems is that it's so expensive to do [AD] and maintenance. To maintain an engine, that's your big expense...It's just pumps and engines, but the engine generator part, that's the real cost" (I14)

While it is expensive to run this type of renewable energy technology, its price is also relative to the nonrenewable energies that they must compete with.

"We can't compete with fossil fuel. Oil at $150 per barrel is when we were getting about 8-9 cents per KW of power. But when it went down to $50, where we are right now or high $40, we can't compete with it, no energy can compete with it. But at the end of the day, environmentally if we're going to drift away from fossil fuels, the alternatives are more expensive. We don't need much, but we can't do it for 4 cents." (I12)

A noteworthy challenge that was mentioned within the interviews was the depreciation of payment programs and policies that incentivized AD electricity production.

> "The biggest issue that we've seen is certain policies have fallen out of favor. Such as power credits; instead of electric credits, now they're gas credits. So in order to meet and be capable of taking advantage of those new credits, we have to do an enormous and very costly upgrade to the facility to generate some of those credits because today, some of those credits are dropping off and the gas credits are coming up...we're looking at a drop off of pure electrical standpoint, a 50% drop off in pricing after 2020 as the law with renewable energy credits." (I3)

Another operator affirmed this experience: "It went from a peak of 6-8 cents per KW to now it's about 3-4 [cents]" (I12). Another respondent elaborated on a similar experience:

> "Now since then, [carbon tax break credits] have completely disappeared and renewable energy credits (RECs) are just a fraction of what they have been. They're much less than what they were originally." (I17)

For further emphasis:

> "We had a problem with getting paid, we were on a variable rate, the power at the time was paying 12 cents and then it dropped to 7 cents, then guess what? You can't pay for that with that type of return." (I18)

With the depreciation of the original monetization strategies, some operators had to quit their AD due to economics:

> "There's a reason why it's not running still. It's not economical. We're lucky to get a penny and a half per KWh. So we're running it below cost...It costs more to run it than what [the utility is] willing to pay for. Some months we make a penny and a half, some months it's three cents. So it's not very conducive to the generator." (I17)

Due to the uncertainty of depreciating incentive programs, one operator stated: "You can't build a business model around it, because it may not be there tomorrow" (I17). Another respondent imparted:

> "For the price, for what it costs to install [AD systems], for the payback it would be much better to invest the money somewhere else. Like you're talking about a 16-18 year payback, which is a pretty terrible investment business-wise." [I15]

The only solace noted by respondents was the promise of government commitment through economics and policies that incentivizes AD.

> "If somehow the regulatory bodies, or government or the nation, whatever. If we're going to make a commitment to renewables, we have to make that commitment of all renewables." (I7)

Some operators pointed to the success of government subsidies working in other states like Vermont:

> "In certain states renewable energy is subsidized pretty heavily and some of that flows back to the producer, and we're not doing that in [this state]. So producing electricity is not a profitable thing, that's why utilities don't want to do it either. Go to Vermont, they're getting paid twice as much as we are, because it's subsidized."

According to the operators, government oversight over how power purchase agreements and renewable energy credits are negotiated would make a huge difference to the success of AD.

Their oversight should also include a revision of carbon credit valuation, which as it stands is disincentivizes food waste acquisition:

> "The [carbon credit] program is written that manure credits apply. I have to separate out a good share of those BTUs generated and only be paid for those from the manure. That's the way the program is written now." (I20)

This all suggests that the economics for AD are a significant challenge for many. If it weren't so economically difficult "you'd have a lot more green energy" (I12).

2.4.2 Motivators/Benefits

With any technological adoption there needs to be a reason for adoption. In this theme, motivators and benefits are described. They are grouped together as they both describe positive attributes. However, in grouping them together, a difference was noted. Motivators help to initiate the adoption process; they contribute to the desire for AD. Benefits are realized advantages by AD, that may or may not have been thought of before the project began. Benefits can be motivators.

The subthemes found within motivators and benefits were many: environmental friendliness, zero waste, income incentives, power generation, feedstocks, heat for water, automation, bedding, nutrient management, odor control, complementary enterprises, and digester-friendly regulatory environments. In order of times mentioned, the motivators/benefits most important to the producers are 1) improved nutrient management (18/20 interviews), 2) odor control (14/20), 3) favorable power purchase agreements (13/20), power production (13/20), digester friendly regulatory environments (13/20), 4) feedstocks and their tipping fees (12/20), bedding material (12/20), heat for water (12/20), 5) environmental friendliness (11/20),

6) awarded grants (10/20), AD incentivisation programs (10/20), 7) automation/ease of operation (6/20), 8) zero waste (5/20) and complementarity of enterprises around AD (5/20).

2.4.2.1 Environmental friendliness

The subtheme of environmental friendliness was mentioned in eleven of the twenty interviews. This subtheme is an amalgamation of feelings towards actions that are environmentally friendly. For example, green energy, sustainability, reducing a carbon footprint, all fit within the subtheme of environmental friendliness. One operator illustrated environmental friendliness by stating when asked why they got AD, he noted that they wanted to be “more self-sustainable” (I14). Another mentioned their reasoning for being involved in AD: “for me, it’s for the environment” (I8). One operator stated their intention to get AD was to get ahead of the environmentally friendly regulations:

> “We knew there was going to be an environmental push at some point and before we found ourselves in some corner by some agency that we should probably do something to move forward that was a better way of doing. We like the way it works. Would we do it again? Yes. I don’t think [we] would really consider farming without one....It is a good way to handle a substantial waste stream in a responsible manner…[and] it’s a good way to sequester gases going into the atmosphere.” (I18)

Two other respondents noted environmental friendliness as a positive effect on internal dynamics and branding. The first operator believed that AD made their business a “real feel good operation because it’s renewable energy” (I9) The second operator saw the benefits of AD truly affecting their ability to operate and branding:

> “[AD] really helps with our license to operate a large family based dairy farm...If we can have odor reduction, better nutrient management planning, for absolute carbon footprint,

perhaps fewer trucks on the road that all leads to our license to operate…[it also has a] powerful impact on cheese marketing and our branding." (I20)

2.4.2.2 Zero Waste

This subtheme was mentioned by five of twenty interviews. AD provides a way to capture value and energy from manure and landfill-bound organics wastes through biogas and digestate. This sense of reducing waste was important to some operators. One mentioned:

> "We've never been the type of farm to just throw stuff away...We really didn't want anything to go to waste. If there's value there, we want to grab it." (I1)

Another operator explains the capability of reducing waste through digestate: "The digester can eliminate waste by putting it into a form that grows more plants" (I7). This describes the way that the digester can transform nitrogen in the feedstock to make a more biologically available fertilizer. One respondent mentioned that their AD helped them so well with their zero waste goals, except:

> "[The] only thing wasted is diesel fuel for the trucks to bring the substrates in and using our load/excavator to put solids in and fix things...and our regular trash" (I8)

One operator appreciated a sense of circularity in their zero waste behaviors as they use rendering wastes, stating that "some of the dead cows from our barns may come back to provide power" (I20).

2.4.2.3 Income incentives

Income incentives are a very important subtheme. Within it, there are three divisions: awarded grants, AD incentivization programs, and favorable power purchase agreements.

2.4.2.3.1 Awarded grants

Ten of the twenty operators mentioned receiving grants that helped them pay for their AD project. While not every operator mentioned where their grants came from, those that did receive grants described their grants coming from federal funding (I18, I19), state funding (I1, I11, I16, I17, I18), non-profit organizations (I15), and private investors (I4). These grants made AD possible. One operator said:

> "If it hadn't been for that grant money, there's no way in the world we would have spent that money...That's kind of what got us to do it: we could get the grant money. And we got the grant money. If we didn't get the grant money we would have never built it…I wouldn't say there was a big desire to want to do it, until the grant money came along." (I16)

Another operator echoed the previous statement:

> "I would [invest in AD] again because it didn't cost me a lot of money up front. Would I go and buy one? Absolutely not." (I15)

One operator mentioned how AD is "kinda like icing on the cake for a farm, it's not a necessity, so if you can get the [state department of agriculture] to pay half for it, it helps" (I17).

2.4.2.3.2 AD incentivization programs

This subtheme was mentioned in ten of the twenty interviews. These programs include "tax credits, renewable energy credits and carbon offset credits" (I3). These credits, similar to subsidy programs, allow for increased monetization of AD systems, thereby incentivizing the development of the AD industry.

Some states have unique incentive programs. For example, the state of California has a biomat tariff, which is a market adjusting tariff (MAT) to incentivize electricity production from digesters (I1). Another state, Vermont has the well-known digester program called the Sustainably Priced Energy Enterprise Development (SPEED) program and the Cow Power voluntary rate program. The SPEED program "offered people willing to build a digester a guaranteed higher rate for power" (I19) so fluctuations in the REC prices could be mitigated and profitability could be guaranteed. In addition, Vermont has the Cow Power program, which is:

> "A voluntary rate subscription by the rate payer. They would give 4 cents per KW on their bill. They'd add 4 cents for the cow power program, which went directly to the farmer." (I18)

This program allows end-use consumers (households) to voluntarily opt in for paying a higher rate knowing that it was renewable energy, a good fit for renewable energy conscious communities.

As noted by some respondents, some of the previous credit systems mentioned can be brokered by third parties (I14, I15, I16). One operator described their broker-negotiated arrangement:

> "We forward sold [our credits] in a 20 year contract...We sold them to another broker on a 20 year contract. The reason we took that, we were guaranteed a set price, we were given a lump sum which helped pay for construction. Instead of selling them annually, and getting a much smaller check. We sold them, in one lump sum...We have to do some reporting, some record keeping to track our gas production and electricity production and whatnot. And they want an annual report on how many KW we made...We are actually running 10% ahead of contract. So what happens, our contract was for 20 years for so many carbon credits and we could either...the contract would end either one of two ways; 1) at the end of 20 years, or 2) if we reached 110% of our contract volume. So we are

actually at the 110% for the 13 years we've been going. So unless something changes we are going to end at the 20th year and they're going to get an extra 10% of credits from us. But that's the risk you take, they could have gone the other way and we could've made less credits, less electric than they calculated we would. And they would've paid us more than what we gave them in credits, so there was a risk in either direction and we took it that way because we got a lump sum check that helped with construction costs." (I16)

2.4.2.3.3 Favorable power purchase agreements

This subtheme was mentioned in thirteen of the twenty interviews. There appeared to be three major power purchase agreements (PPA) described: buy-all-sell-all (I3, I8, I19), net metering (I6, I11, I12, I14, I15, I16, I17), and remote net metering (I4, I10). The buy-all-sell-all PPA describes a scenario where an operator sells all of their power to the grid, and buys back power at a lower rate. One operator further described the situation: we are "paid a higher rate for our green energy than we have to pay to operate the plant. So it behooved us...It was much more lucrative for power generation" (I3).

A net metering PPA describes a scenario where the power generated by the digester is used on-farm or credited towards the total on-farm energy consumption, thereby displacing consumption of electricity from the grid. If the farm does not need the energy, "it goes back out on the grid" and is sold (I16). One operator described the PPA:

> "Net metering allows for costs to be displaced, instead of striving to make money off electricity...If you have a need for the power, and you can't get any more (money) for the electricity from the utility, it might be best to use it onsite to offset consumption." (I11)

It does seem that a less than optimal price paid motivates the operator to use the electricity made as much as they can with a net metering PPA. In one digester operation, a net metering PPA allowed for a unique connection to the grid: island mode. They described their connection:

> "I've heard that some people are tied to the utility, so when the utility goes out, they can't run their engines….Nope we can. The way we set things up, now it cost us an extra $15,000 to do that. But we have a radio controlled breaker, that when the utility goes out, it communicates with the generator and we break ties from the utility and we keep on running the farm...We had a good utility to work with and that's why that happened." (I16)

This same operator mentioned that they had island mode thanks to their utility:

> "Our utility has been extremely good to us, we worked really well with them. They are very diligent at keeping things constant and consistent with us. And most of the time I have problems in their utility grid before they do...They actually gave us some things that weren't required in our net metering agreement so that's how it's cash flowed because we're getting a good price for any power that we sell back" (I16)

Having a good connection with a utility is positive.

The third PPA agreement mentioned was remote net metering. This arrangement allows the power produced by the digester system to be credited to an off-farm site to displace their use. To an electricity consumer with high electric prices, these credits can be marketed at a lucrative price.

2.4.2.4 Power production

This subtheme was mentioned by thirteen of the twenty interviews. One of the most beneficial products of AD is biogas, which can be used to create electricity. This is, as mentioned in the interviews, a major motivator and benefit. In comparison to other renewable energy technologies, AD has some advantageous characteristics, as one operator described:

> "My digester can produce electricity 24/7, you're not going to get that with solar, because it gets dark, and not with wind...With the digester, you're constantly producing, unless you're not constantly feeding it, it's one of the most efficient methods of creating electricity and disposing of waste. Wind and solar don't dispose of anything. It just theoretically enhances waste, because the people who use the energy, do what with it? Create more waste. So digesters actually complete the cycle." (I7)

Another operator reiterated this statement:

> "When we hear about solar farms, I can kind of yawn because the amount of electricity and the dependability and the online performance of digesters just spanks much of the renewable industries…[the gas produced] each day is equivalent in BTUs of 1000 gallons of diesel fuel...so every year the value of that digester sits at between 3.5 and 4 million gallons of diesel fuel equivalent." (I20)

The sheer quantity of electricity production is an important aspect of AD. One operator mentioned that they are "running at capacity all the time" (I16). One operator mentioned that they can produce "enough electricity to operate the whole farming operation and 30-50 additional homes" (I14). Another respondent claimed that they "can create enough power to power 400 homes" (I19). And another mentioned producing enough power to "power about 1200 homes" (I8). One operator told of a time during a massive storm that knocked off power for a couple weeks that their "generator ran flawlessly. So, we did not miss a milking. While other local guys had to go rent generators and they had to get it set up and run and essentially they lost" (I17). The power generation capability should not be underestimated.

2.4.2.5 Feedstocks

As a subtheme, the benefits of feedstocks were mentioned in twelve of twenty interviews. The benefits of feedstocks are multifold; first there is a bountiful and welcoming supply of feedstock for digesters, second, tipping fees provide a source of income, and third the feedstocks improve the digestion system.

The "organic waste stream that's available is incredible...We turn down calls regularly" (I12) one operator stated. The feedstock market has proven to be very demanding for an organic waste sink like a digester. Another operator added the reaction they got when they originally tapped a new feedstock stream:

> "I went into a [local] supermarket, and they had a food grinder in there and they grind it up themselves and they didn't believe a farmer existed who would use it, within an hour radius, not to feed the animals with, but not use it as garbage, but for use it as energy. You'd be surprised at how much "wow" factor they actually had." (I4)

Organic wastes are difficult to dispose of for many waste producers, so digesters satisfy a market demand. The fortunate part of digesters is that "there's no shortage of what you can put into a digester and use to create natural gas" (I20). Additionally, "people just don't want to deal with [organic wastes] or send it" and some WWTP "just don't want to deal with it either" so feedstock producers will eagerly seek AD (I17). This leads to a great potential for diverting organic waste streams towards renewable energy production.

When accepting organic waste feedstocks, a handling or 'tipping' fee is asked from the feedstock producer. One operator described how tipping fees work:

> "We're taking [organic wastes] out of the landfill and it's mostly cheaper than the landfill. We [have tipping fees] on purpose, of course, to make it economic for everyone.

> We want to have stuff come here rather than the landfill, that's kinda a no brainer. So the tipping fees are lower." (I8)

Tipping fees and their resulting contracts are the basis of competition and acquisition of feedstocks from the organic waste market. One respondent described their competitive behaviors in order to secure better feedstocks and bigger tipping fees:

> "We are able to expand our radius to get into a bigger city where they pay bigger money to get rid of the waste. We can swoop in, make them an offer, put trucking into a mix of things, and we're still more affordable than others." (I4)

In addition to tipping fees, in some states there are tax discounts "for every gallon of substrate you brought in...For the person sending the liquid, and the person receiving the liquid receive a tax break" (I17).

These feedstocks can have positive effects on the management of the system as well. One operator stated that the feedstocks that "we take creates additional gas above our baseline, so that's additional revenue for the power sales" (I3); another operator mentioned that the feedstocks "double the gas production" (I14). These statements about feedstocks are consistent with the statement that feedstocks "make the digester that much more efficient" (I17). Additionally, in one respondent noted that they accepted high liquid waste whey as a feedstock, which "waters [the manure] down and it gets [the manure] through the pipes" (I19), which contributes to less pump blockages.

2.4.2.6 Heat for water

The subtheme of heat for water was mentioned in twelve of the twenty interviews. One operator described this subtheme:

> "There's a lot of things that have saved us a lot of money with the digester that we hadn't factored in. One of them is the heat that we get off of it. That's worth a lot of money." (I15)

One operator explicitly stated that costs saved as "$40,000 per year to heat hot water" (I12). This heat is captured from the engine that is combusting the biogas for energy. The ways that the heat was being used are notable. One operator outlined their set-up:

> "Two or three of our farms are grabbing heat off of it and heating multiple buildings...Hot water coming off the engine is being used in radiator or baseboard heat in multiple buildings…[and] heating my home with it." (I4)

Several mention using the heat to "heat the digester' (I6, I8, I11), heating personal homes (I4, I5, I15), and heating the dairy facilities (I4, I12, I14, I15, I19). One even mentioned "selling the heat to neighbors, there's so much heat to get rid of" (I5).

2.4.2.7 Automation

In six of the twenty interviews, operators mentioned automation involved with their digester, easing their responsibilities and making AD systems more manageable. One operator expressed the positive effects on the working staff automation had: "[We have a] fully automated facility that we can control remotely. So we don't have any night crews or second shifts like that" (I3). Another revealed what the automation controls:

> "Basically all the pumps are scheduled to work at a certain time, at a certain flow at a certain time, feed the digester at a certain time, and put products into the lagoon at a certain time. All that is programmed into the PLC [programmable logic control] system and the system runs itself….Allowed us to basically have a man and a half." (I7)

Another asserted that their engine was also automated:

"Luckily I can set up our engines to where they run [by themselves]. Their power will increase when the gas does so overnight if we get a sudden drop or decrease in gas, then the engines will either rev up or slow down. That just increases the efficiency of our engines not burning our methane off." (I8)

Due to automation, one operator disclosed their confusion at other's staffing challenges:

"[The digester] takes care of itself. I monitor it, but there's really nothing to it. So often, people hire a person to [manage the AD], and I'm like "what?" I spend less than 5 minutes a day on it, unless there's some sort of maintenance required. There's nothing to do besides monitor a couple numbers to make sure it's functioning." (I14)

Automation of mixers, pumps and the engine offer a positive way to reduce management challenges and can reduce strain due to hiring, training, and retention.

2.4.2.8 Bedding

As a subtheme, the use of manure solids for cow bedding was mentioned in twelve of the twenty interviews. One operator mentioned that the manure solids "eliminated our bedding bill" (I5). Another respondent exclaimed "look at the bedding costs we save...something in the vicinity of $100,000 a year in bedding costs" (I18). Even more than costs, this bedding is of high quality, far superior than undigested manure fibers:

"The biggest benefit is [the digested manure fibers] won't propagate. Once you've taken it to the high temperatures, it won't support bacterial growth the same way composted manure will. It isn't perfect, but it's much lower in its propagation of particularly mastitis bacteria. And it dries out better, and it won't hold moisture as much as composted manure." (I3)

Another operator agreed with the previous statement, noting their appreciation for having "quality bedding that was pretty much pathogen free. [AD] kills a lion's share of pathogens" (I12). One operator mentioned another use of methane: using it to fuel the dryer of the manure solids (I20). It appeared that most operators are not selling the bedding on a commercial scale:

> "We sell some to gardeners and greenhouses and that sort of thing. But primarily we are using it for bedding on the farm. We are not actively marketing it. We have a lot of people coming here because they know we have a digester and they like it because it is a good soil amendment, no weed seeds, the odor is pretty well gone, and they know they get a good deal. We try to keep the community happy." (I18)

Another respondent mentioned how providing manure solids to the community is a challenge and also a gift to the community, agreeing with the previous excerpt:

> "I have a couple of businesses that I can sell to without collecting sales tax, so I'll sell it to them. Anybody else, it's a gift. Which I do occasionally do, because it makes for good gardens. And it makes for good neighbors." (I19)

2.4.2.9 Nutrient management

As a subtheme, nutrient management was mentioned in eighteen of the twenty interviews. The discussion around the fertilizer value of digester effluent revolved around the fertilizer value of the digestate, the displaced costs, the improved ease of spreading, and sales. As one operator put it, AD "has allowed us to take the manure headache away and put it through the digester, process it, get it into a fluid format and apply it more thoroughly" (I7). The digester increases the fluid concentration of the loaded organic materials (before the separation of the solids and liquids). Separating the solids from the liquids "enhances [ones] ability to mechanically handle the wastes post-digestion. It changes the viscosity" (I10) and "it makes more room for the digestate to go in [storage basins]" (I8). With the less viscous effluent,

> "You can pump manure that's gone through the digester because it's slipperier...You can pump that as far as two miles out into the field through a transport line and run a dragline operation utilizing a tractor that reduces compaction on the soil." (I18)

Using pumps and transport lines, as one operator put it:

> "That allows me to handle it without trucks on the road, without traffic, without high fuel costs and things like that. I can simply put it through a pipe. And inject it into the field." (I10)

While it may be true that AD is "just a better way of managing our manure and nutrient streams on the farm" (I11), it also produces a superior fertilizer. One operator described the fertilizer benefit like this:

> "One of the side benefits besides the paycheck of digestion is the decomposition or the breakdown of the organic material and with that being said, the effluent, the NPK is more available the first year of application. So it's a more immediate uptake of plant usage. If you break it down, the NPK are more usable, which helps lower your nutrient loading on the farm. The more the plant takes up and photosynthesizes and produces a crop, allows for levels to maintain and keep climbing...You got a lot of manure and you need to have a manure application plan to be good stewards of the land." (I6)

Another further explained:

> "So those nutrients are now [post-digestion] in an inorganic state and that has allowed them to be in a mineralized state and they adhere more readily to the soil, the volatile components have been broken down in the digester system. And it allows us to apply

those nutrients evenly to our alfalfa, following the first crop, we have an alfalfa harvest at the end of may or first week of june, we applied 7000 gallons an acre to roughly 600 acres of farmland. So we applied around 4 million gallons of manure. And that does not burn the alfalfa or grass in those hay fields." (I20)

According to the operators, the nutrient value of the manure stream increases with digestion. Another operator added that the digester helped with pH management of soils as well:

"There's a lot of things that have saved us a lot of money with the digester that we hadn't factored in...One is, in [our state], we have acidic soils, so we crop farm about 900 acres, and we would buy a couple hundred tons of lime. Most of our fields would get like a ton or two ton to the acre every four or five years. So when you're putting manure on that has a pH, if you're using a lot of sawdust for bedding, it's going to have a pH of 6 or 5.5. The digestion process changes the carbon in the manure to carbonate, which raises the pH. So now the pH of my manure is about 7.8 and we haven't bought any lime in 3-5 years...That was a savings that we hadn't anticipated." (I15)

This high quality soil amendment positively affected one operator's farm costs and management practices:

"It is so nitrogen and phosphorus rich that [the farmers] don't need to buy the NPK fertilizer, which is very expensive and pretty corrosive and they actually don't need to switch between corn and beans. They just grow corn every year to make feeds for the cow for silage." (I8)

Another operator mentioned that "[the digestate] is better than the fertilizer that we used to buy" (I5). In addition to cutting the on-farm commercial fertilizer bill, when shared it also makes the neighbors happy:

> "Farmers around us love it. It cuts their commercial fertilizer bill and provides more than a commercial fertilizer can because you can get the organic matter." (I6)

Several mentioned sharing the liquid digestate with neighboring farms (I6, I8, I11).

2.4.2.10 Odor control

As a sub-theme, the benefits of odor control were mentioned in fourteen of the twenty interviews. In terms of odor control, AD has allowed for nutrient management practices that are considerate of neighbors' odor tolerances:

> "Now we're able to spread our nutrients on our crops throughout the growing seasons without making everybody in the neighborhood mad, because it stunk so bad [before the digester]. Spreading raw manure stinks and nobody likes that. So by putting the digester in we were able to spread the nutrients on growing crops of hay and corn, without offending the neighbors so bad….For odor control, it has worked well." (I13)

Another operator echoed this message with, "On the overall consensus, the majority of the year, it is drastically better than it was before digestion" (I6). This is good "for political and public reasons" (I9). One specific operator even mentioned that "my odor complaint file is empty" (I3). In addition to "better nutrient management planning for absolute carbon footprint, perhaps fewer trucks on the road," odor reduction "really helps with our license to operate a large family based dairy farm" (I20).

2.4.2.11 Complementary enterprises

As a subtheme, AD was mentioned to complement other enterprises in five of the twenty interviews. One operator described it well:

> "[AD] allowed a few other things to happen in the business that wouldn't have happened if we didn't have it. This milk waste that we bring in, all of a sudden we take all the waste

from the milk plant, which is another business in itself and if we didn't have the digester to start with, that wouldn't even open up the door. So there's ancillary things that appear on the doorstep that wouldn't have happened without the digester...So all of a sudden you can't contribute this all to the digester, but because of that we had some opportunities to present themselves that turned out pretty lucrative...I would have never have expected it in 2011 and 2012 when I was doing the research. It was a real investment but the things that it opened the doors of were huge." (I12)

Another operator mentioned that when upgrading their farm, the digester was incorporated and facilitated other additions:

> "We built a couple cow barns and heifer barns and some bunker silos, and a shop and an office, and we knew that if we could bring in a manure digester, and incorporate that with all the new buildings, then our manure system, our hot water loops, our electrical infrastructure, etc. could all be coordinated and incorporated, and that's what we did...It helped with the natural flow around here." (I20)

2.4.2.12 Digester friendly regulatory environment

As a subtheme, digester friendly regulatory environments were mentioned in thirteen of the twenty interviews. In this subtheme, the government seemed to provide opportunities for AD by creating supportive regulations and renewable energy goals. One operator expressed their regulatory environment that:

> "In the more recent years, the regulatory environment and the permitting climate, all that has become much more friendly. [our state] has been much more aggressive in the past three years in getting digesters built. So they've really streamlined the process." (I1)

In this same state, they set out 100% renewable goals, which further pushed renewable energy development (I2). In several cases, government programs and laws created and streamlined power purchase agreements that were favorable for renewable energy producers like AD (I3, I4, I6, I10, I11, I12, I15, I18, I19). For example, one state had a ‘net metering law’, which:

> “Allows farms that have onsite digesters with generation to net meter that power up to 2 MW. Our generator is about 450 KW. So we’re under the max capacity, and we’re allowed to sell and buy power from the grid depending on our demand. So at the end of the month, we’ll either have a credit back onto our bill or a purchase of power.” (I11)

Another state had a similar net metering law, which one operator describes why it serves them well:

> “We have a net metering law that [our utility] is required to take. There are no negotiations, you call them and tell them, and they come and hook it up. It is nice. [Our state] has probably more digesters than any other state and it’s probably because of that law. You hear people in other states that say they’d like to put in a digester but they can’t get their utility company to take it.” (I15)

Another state, Vermont, has the very lucrative SPEED program and 100% renewable goals:

> “Vermont had a very strong program called the SPEED program, which offered people willing to build a digester a guaranteed higher rate for power...The utility company was bound to it. They had to agree to take a certain amount of renewable energy that’s part of the SPEED program. Vermont has this goal to be 100% or 90% renewable by 2050. So all the utilities have to agree to this, and as a result they have to go find those renewable energies. They come up with a number they think that they can pay, with what they think the market is going to bear. We locked into 16 [cents per KWh], I think new ones are

> only locking into 12 [cents per KWh]. But still what people pay nationally, that's still a lot of money." (I19)

These utility policies do not necessarily have to be externally regulated policies. In one operator's case, the utility had an internal policy that was quite helpful:

> "Our coop [utility] had a policy that if we were upgrading an existing service, we were single phase power and when we put this in, we had to go to three phase power. They had a policy in place. So if you upgraded an existing service all you paid for was the material, they put in the work for nothing. So we upgraded a mile and a half of the utility line for a low cost. Some of the public utilities, some people are spending 100's of 1000's of dollars to upgrade their service to put in a digester. And we didn't have to do that, because that wasn't the policy of our coop. So that was one huge benefit that we had that some of the other digesters built at the same time didn't." (I16)

Not all policies that benefit AD come through the utility. In one state, organic wastes are "not allowed [legally] to be dumped down the sewer" or go to the landfill (I4, I5). This created a newly founded and unclaimed organic waste stream for tapping by AD. One operator described why the organic waste stream diversion to AD became more beneficial for feedstock producers:

> "If [feedstock producer] do dump it down the sewer line, they have to add water - the answer to pollution is dilution - and in turn if something is real fatty or oily or whatever, they have to purchase more water, put the water with the waste, increase the cost of the waste to get rid of it, and then they send it down the sewer if they can. But most of them can't do that. In turn we would prefer it as dense as possible. We have the ability to take solids or liquid, but we prefer liquids and we can take it, a lot of it will pump through a

six inch hose, we'll take it. In turn, they don't have to add water to our system, we come in and clean it up." (I4)

These regulations created friendly policy environments for AD development.

2.4.3 Knowledge

The theme of knowledge is both about how operators learned and also the lessons conveyed in the interviews. This theme can be broken down into nine categories: learning, digester systems, success factors, feeding and feedstocks, PPAs and monetization strategies, gas and engine management, digestate and bedding management, and division of knowledge and responsibilities.

2.4.3.1 Learning

This subtheme was mentioned in eighteen of the twenty interviews. How the operators learned and their level of experience was a byproduct of the research. With such depth of experience, and the possibilities of others joining to contribute to the industry, the ways operators learned was important. As mentioned previously, the time the farms had their digesters varied from 1 to 15 years, with a mean of 7 years, median of 8.3 years, standard deviation of 3.7 years and for a sum total of 157 years of experience by the farms. Not all operators were part of the full experience of the AD on the farm. Nonetheless, there was a great deal of experience amongst the operators.

The interviewees demonstrated that enthusiasm plus experience leads to wisdom. One operator with fifteen years of experience proclaimed themselves "super passionate about AD" and had "worked on dozens and dozens of [AD systems] up and down the Midwest, Ohio to California" (I1). One described their learning process:

> "It was basically me learning. Trial by error...We started making gas in the late summer of 2013. And obviously everything you're learning at such a fast rate, trying to watch and pay attention...Now, life is easy. We learned a lot that winter, the next winter was not as bad, it was still pretty cold. But some changes that we had done definitely helped. I went ahead and furthered some ideas after operating it after more than a year and a half. And after that it's really easy peasy now." (I6)

Another respondent further explained how one can learn about AD:

> "It's all just lots of hours watching and seeing what happens...I can't sit here and tell you how to run a digester. I can give you an idea. But you have to sit and watch how the bacteria and the feed, and how everything works in your particular situation. No two...it's like a snowflake, no two are the same." (I16)

This latter comment that 'no two are the same' was reiterated by another operator, who emphasized that knowledge comes from "understanding that there is no one way to do [AD]" (I7). The differences in feedstocks, environment, management strategies, design of digesters, etc., these characteristics of digester systems create uniqueness that makes knowledge building both general and specific for the situation. This comes with experience and with enthusiasm. One operator put it like this:

> "If you got a person with interest, [learning] is easy. You know, the right person for the right job. The challenge is finding the right people....[because] if you don't do your homework, you'll get yourself in trouble quick." (I9)

When finding the right person, another operator expressed the value of experience:

> "Just as much as someone may graduate from college and have the best degree and background, it's still hard to beat someone who has 30-40 years of hands-on

> experience...it’s similar to feeding a dairy cow. So if I asked a nutritionist how difficult it is, the young nutritionist may say “it’s quite a challenge”, but a seasoned one may say ‘it’s not that difficult, I use sesame and here’s the products that work’.” (I20)

Digesters in the US are a relatively new industry. So finding experience can be quite a challenge. Some operators circumvented this challenge by heading to countries that had many digesters to learn more:

> “So, I ended up going to Germany and Austria to go see some digesters and I was over there for a week. We looked at a dozen different projects. We went over with a small group of farmers within the area and we looked at digesters that were producing electricity from 80KW up to 1 MW. So we saw both ends of the spectrum. [Then we] came back to [our state] and discussed how we were going to do it. We had Germans over here, two different times for a couple of days each time, full days in the office, trying to go over the conversion for pricing from metric to US standard.” (I18)

Another mentioned “relying on US biogas to teach us what to do” (I7). Industry groups like US biogas may be great ways to develop a working knowledge of AD if traveling abroad is not an option.

2.4.3.2 Digester systems

As a subtheme, digester systems were mentioned in eight of the twenty interviews. This subtheme includes descriptions of digester designs, and reasons for centralized vs individual farm-based AD systems. In the interviews, there were three types of digesters described: covered lagoon (I1, I2), plug-flow (I3, I17), and complete mix (I7, I20). Covered lagoons, as the name implies, is a traditional manure lagoon/storage basin that is covered with a gas impermeable sheet that helps to capture the gas for use in generators for energy. One operator described covered lagoons as:

> "The simplest form of AD available and... the most economical form of digesters available at least in CA... In WI, freezing temperatures make it difficult to maintain 98 degrees in digester, so covered lagoons are not popular" (I1)

Usually they are not heated, so the ambient warm temperatures of California allow for this simple digester system to work.

The next digester system type is called plug flow. They are minimally described as "U shaped" (I3) or "horseshoe shaped...where the manure goes through a big basement" (I20). Another described them as "very simple systems compared to [complete mix], which has essentially all the bells and whistles" (I17). "There are quite a few plug flows built in the Midwest" (I20).

Complete mix was described in detail by one operator:

> "It's a complete mix system, 1.2 million gallons tank, sits above ground. It has a fabric dome. It's flexible. What happens in there is that we have around 22 ft of liquid, 22ft tall of liquid in the tank and as gas accumulates, there's an inner bladder that traps the gas. And then between the inner bladder and outer bladder is air and there is an automatic system that basically keeps the outer bladder round. So if there's more gas we expel oxygen, if there's less gas, we put in more oxygen to keep the round shape. But the inner bladder traps the gas." (I7)

Usually, these systems, as the name implies, have mixing systems like large propeller blades to homogenize the internal contents and improve the digestion and biogas potential of the system.

There is a growing trend of creating centralized digester systems, where multiple farms contribute wastes and feedstocks to the digester for gas production. These systems are relatively uncommon though compared to individual farm systems. A couple operators describe why this might be the case:

> "I don't know if there was anybody close enough at that time that would have wanted to go in on it, and it would have been complicated and expensive to move material to it because of the location. Nothing's impossible, but it would have required a lot of pumping of distance, or hauling. And the complication of land applying the nutrient part… I just don't think that would have been a good thing for our location and what we were doing." (I14)

Another mentioned:

> "Now we don't want to move manure into the home farm. Then we might have to move [manure] 6-7 miles into the home farm and then we have to turn around and move it 6-7 miles back out to put it on the fields and that's way too expensive...We had no desire to get involved [in centralized AD]. Too many people, too many irons in the fire can make things complicated." (I16)

One operator discussed the possibilities of scale in relation to digester design:

> "Recognize if it takes a certain volume, don't try to reinvent this on a smaller scale, unless you really know how. For instance, why would somebody with a 50-100 cow farm have a hard time competing with a 1000-5000 cow farm? There are certain reasons. Why does a certain sized digester not compete with another digester? How does the land base getting further away from the digester [affect success?] How much more does that cost as

> compared to not having to truck that post-digester effluent away from there compared to pumping to a nearby lagoon? How about the cost to bring in that digestate?" (I20)

2.4.3.3 Success factors

Success factors and the lessons people have on success were mentioned in thirteen of the twenty interviews. What might be important to note upfront is that:

> "What's interesting about digester technology is that it's not new technology. It's really not. It's a very simple system when it comes down to it. And I think we've proven and there are dozens and dozens of digesters that have been operating for years. The technology is proven" (I1)

Digesters work. Understanding the system is imperative. However, as this operator suggests it can be easy. There will be challenges, as one operator explains how to overcomes those:

> "You know everything presents itself as either an opportunity or a challenge depending on how you look at it...You think it's going to function when you're building it. And that always doesn't...When you started operating that could have been a good decision or a bad, but you gotta make do with what you have." (I6)

One analogy that seemed to help in management of AD was repeated was the comparison between AD and cows or just generally a "living breathing organism" (I2):

> "You gotta remember, a digester is like a cow. It's a living thing. It's more complicated than a cow...You gotta keep the bacteria happy, as well as all the mechanics and electrical components that don't like to work all the time either. So, you've got both a living object and a mechanical object and they gotta work together." (I16)

The infrequent miscouplings of the biological from the mechanical lead this operator to suggest keeping "a list of spare components that most frequently go bad," and keeping it simple: "Keep it going the way it's going and keep it simple. It's not an additional expense and not an additional headache" (I16).

One operator raised a question on the role of supervision, "are you going to sit there and monitor every load that comes in, or are you going to kind of self-regulate?" (I17). Another operator answered that question:

> "Having a digester is like having a small boy around: he may be the best kid in town, but you're not going to turn your back on him without checking on him frequently. The same with a digester. You're not going to turn your back on it without checking on it frequently. I'm talking about a half a dozen times at least. And that's when things are going good. You've just run through, you have a look at the gauges, the temperatures, the oils, the water, just ensure that everything is going normal or not. If you fail to do that, you're inviting trouble. And if you fail to do that, you'll find yourself up to your chin." (I18)

Supervision without micromanaging seems to be a balancing act to make sure that the AD is working correctly.

A success tip suggested by a couple operators was related to priorities. One operator described their priorities:

> "At the end of the day, the dairy has to run. And everything has to run around the dairy. The dairy is not going to run without the digesters...Our objective is to milk cows and have it that way" (I2)

The dairy being a priority, especially because it is the main source of revenue, is important. Another operator emphasized this priority:

> “We’re going to look at milk first. The digester is probably 5% of our total income and that’s with the power sales, the sales of the credits etc. it is however a very consistent paycheck, unlike milk which sometimes is not.” (I19)

While the dairy is a priority, it was reinforced that responsibility to manage the nutrient stream that leaves the digester is still vital, as one operator noted:

> “One of the things we’ve also discovered while researching the digester is that very few companies pay attention to the back end. They put it in the lagoon, [they say] ‘we’ll spread it later,’ but if you don’t account for that you’ve got to do something with the effluent. It doesn’t disappear. If you don’t account for that you’re hamstruck. You're going to struggle with that, and basically constrict your element of growth.” (I7)

The message conveyed was to pay attention to what makes dairying work, but also pay attention to managing the nutrient stream post-digester. Additionally, attend to the biology and the economics of the system: “The economics and the health of the digester have to go hand in hand. You can’t do one without the other” (I9). One operator expressed a warning:

> “Let me tell you like this. If anybody thinks that they're going to put a digester on their farm and get rich. They’re making a mistake. That’s not the reason you get a digester on your farm.” (I8)

Another operator outlined their streams of income:

> “We have four revenue sources with our digester: 1) the sale of electricity to the power company, and it’s about $25,000/month worth of electricity. 2) We also have the value that we put out in the manure fiber, that’s $20-25,000 a month that we allocate to our manure fiber or our dairy herd. 3) The third source of revenue is tipping fees. We don’t allow products to come into our digester without collecting a bit of a tipping fee. Just like

landfills don't let stuff coming into the landfill without a fee. That adds 2-3000 a month. 4) The fourth source of revenue is the value of heat off the digester. Not only do we heat those tanks to 100 degrees Fahrenheit, we also take off that heat and use it to heat the house on the farm, and the woodshop, where my 91-year father hangs out part of the time. It's also used [to heat] our main farm shop and our office building, and the hot water for the nursery facility. We even have a direct hot water loop to the wash bay. So, we are able to transfer that heat to the water that goes to the pressure washer and the wash bay." (I20)

To appreciate the revenue streams that come from AD, the respondents reinforced that one must have a need for the products (electricity, bedding, heat, etc.) and have a power purchase agreement that pays well. As one operator described:

"We use all of those things [electricity, steam, cooled water, bedding], right? So that is why our digester has been so successful for the past 15 years, while other digesters were not. They didn't need all the power in house and there were no purchase agreements in place with the utility to give them a decent rate for the power. So they made this massive investment, but they have no way to monetize it." (I1)

One needs an efficient and straightforward way to monetize the AD. One operator discussed their specific suggestion for improving the first revenue stream: energy production and profitability.

"The key to being profitable is to be efficient. We are able to extract more power out of a gallon of manure than any other digester around...We handle manure differently than many operations...The manure sits on the ground less than 8 hours before it's in the digester. So from the time it's excreted from the cow, it's in the digester in less than 8 hours. And I think we're far less than that actually...The more time, especially in hot weather, you're just losing gas production capability of the manure exponentially. It happens very quickly." (I3)

AD projects are expensive, so the economics matter. Some strive to acquire funding to help invest in an AD. One operator had a word of warning:

"So, if the funding is available, and you have the ambition to go for it, go for it. Just make sure you get your performance up, don't fall into the pit of thinking that once it's built it's going to start cash flowing because it's a challenge. So you could [use] say 5-10% of your initial costs on your feasibility studies. But, that's just a start. Once you're milking a couple thousand cows you're pretty well committed for the rest of your life." (I20)

When deciding on AD and as the enterprise develops, one operator noted it is imperative to "take a step back and look at the financial model and the biological model" and ask yourself "are we comfortable with this? Will it pay or be close to paying?" (I20).

One operator emphasized reputation and general public relations:

"The former operator [of a digester over in Michigan] ran out of money, had the tanks full of manure, set the main switch and walked out. It takes you about a year to clean out the pumps and tanks and everything settles. And you [the operator who took over] go around to the people who provided you feedstocks in the past, and they have a bad image of what can go on. And pretty soon, even though you're a completely different individual, you do not have a good relationship with government officials, wastewater treatment plants, or those that provided you with the feedstock." (I20)

Trusting business agreements, through feedstock contracts and PPA's helps to create continuity in the support network around the AD system. In addition to managing the expectations and reputations of those directly in the support network, it is also good to maintain transparency and educate the public surrounding the farm. This is a challenge, as expressed by one operator:

> "I think the most important thing is not being reactive. I'm very careful when I answer people who start attacking us on Facebook or front porch forum or any other social media. We're not on twitter or instagram. I'm very careful about how I word my responses. I try to do it from an education standpoint. I never insult anybody, or their ideas. It sometimes takes me 3-4 days to really sit down and write a response. I don't always have the answers, and I have to reach out to my guys in the field or go to extension and say "I know this is what we're doing. I know this is why it's good. Can you please express this in a way so that a 10th grader can understand it"...[The extension agents] have always been very helpful in my experience; they very quickly shut down the negativity. People are way more interested in hearing you when you're kind and polite and understanding, then if you get angry. I think it's important to have somebody like that upfront. I hope that I wouldn't say that to one of my brother-in-laws, he's kinda a hot head." (I19)

Farming and AD do have a people oriented part of the business, and it's important to have someone with diplomatic skills in communication and negotiation roles.

2.4.3.4 Feeding and feedstocks

As a subtheme, feeding and feedstock knowledge was mentioned in eighteen of the twenty interviews. This subtheme can be loosely divided into lessons on feeding styles and strategies, feedstock selection, tipping fees, and carbon credits.

There is a spectrum of feeding styles. On one side we have those that only accept the wastes created by on-site dairy and/or animal wastes to those who accept feedstocks as their primary substrate for digestion. The former management style is described by the excerpt:

> "If we [receive less organic wastes] from the cheese plant, the biogas yield drops. So, you know, I don't know if that's really a challenge and instead, you know, we take what we can get. Right? It's like sitting on the nose of a freight train and you're going to take whatever comes. You can't stop the train, right? I can't dictate what the cheese plant does. I just take what they give me." (I1)

This management style finds itself at the whim of the waste producer. It may be a consistent supply of waste whey and manure, but the operator does not have much control over what comes. This may inhibit maximum biogas potential. On the other side of the spectrum is a digester that takes a large proportion of feedstocks as compared to manure. One operator described a nearby digester that did this:

> "They are having some issues I am aware of at [the state] technical college...They were taking about 49% food wastes, and their digester gas was all over the place. Because you don't know from week to week what you're getting." (I19)

A feedstock supply can fluctuate with this style and what is important is consistency. Feedstocks can also provide improved biogas potential as compared to manure, but also increased risk for biological upset, as described in the previous excerpt. What may be the best of both worlds is to have a consistent base supply of on-site wastes balanced with a consistent supply of feedstocks. This seems to be the feeding style of most respondents.

If one is supplying feedstocks, understanding what to feed the digester is important. The interviews described several lessons on feedstock selection. When first deciding on a feedstock, one operator outlined the important questions they ask before accepting them:

> "What benefit is it going to have? Is it consistent and what's the byproduct out of it? In other words, what are we going to utilize out of it and what's going to be left? Because we have to field apply whatever is left. What benefit does it have to the whole system?" (I14)

As mentioned before, one must consider the back end when accepting feedstock inputs. Another operator reiterated their way of considering the back end, "checking the nutrient content of [the feedstock] and what nutrients that's bringing on the farm" (I13). Testing also helps to assess the ability of the digester to produce gas by understanding, "how many BTUs are left in the manure [at digestion], and in the product when it comes out the digester" (I20). Another lesson to remember is that even with feedstocks, you still need manure: "you have to have cow manure. It seems that without cow manure things don't work very well" (I13).

Good feedstocks, as one operator described, are:

> "High energy, clean feedstocks, like grease, sugars, ice creams. Something that is easy and digestible without too much hassle...Anything that has a complex carbohydrate or hydrocarbon, grease or sugar. Proteins are not necessarily the best, but we can digest them." (I9)

In addition, the chemical oxygen demand (COD) is an important indicator of the quantity of biologically degradable organic matter in the substrate:

> "A higher COD is anything above 100. 300 would be an ideal food waste...We sometimes get biodiesel wastes and that's in the 300 range...100-300 is an acceptable range. Ideal is 150. Because then you can put the volume through for as much gas as you can get and it's not hurting the digester...The cranberry [concentrate] measured about 650. So, it was like, "boom!" It was ready to light on fire." (I9)

Another operator described their ideal consistency: "We like liquid products, anything that flows out of a truck. Basically that's our best product. And if it doesn't have any debris in it" (I13). Inorganic debris can be hindrance with AD, especially as inorganic/non-biodegradable substrates do not produce biogas. One operator outline how they prevent contamination:

> "[The feedstock suppliers] have to do a 45 page audit before they come to us...They have to check all the drains and all that, they can't dump nothing down there accidently or any of that accidently. It's challenging for them to get anything past us." (I4)

In addition to what is fed, there is a certain technique to how to feed the digester. One operator report:

> "That was interesting learning about how those bacteria worked, or how that feedstock worked with the bacteria in the digester...If you feed the bugs properly, they'll perform and make gas" (I13)

What seems important to 'feeding the bugs properly' is consistency of quality and quantity. One operator elaborated on their measured technique for maintaining consistent feeding:

> "We avoid slug feeding the digester. So if you slug feed it, in other words, if you put all of that product in it once, you're going to spike your gas production. What's going to happen is it'll taper off; it'll fall on its nose at some point. So what we try to do is meter it in, so we have a relatively consistent gas production. So what you need is ample storage,

> and everything we handled is pumped. We are not handling any solids or anything like that. Everything we handle is mixed into a slurry and pumped." (I18)

Mixing is important for making sure that the quality of the feedstock is consistent. By paying attention to mixing, the feedstocks are made homogenous so then there are no pockets of high and low BOD/COD areas in the incoming conglomerate. To emphasize how important mixing is for consistency of quality, one operator described their set-up and their series of mixing pits to ensure homogeneity:

> "We have a main mixing pit that's actually open and the trucks dump in there. And that's where we mix our solid manure in. That is where the direct manure line actually empties into, that direct mixing pit. And the next chamber that it goes to is just a larger mixing pit, called the equalization chamber. And there's three mixers and we have all of our mixers run off the electric. They basically look like a boat propeller, that's basically how big they are. We use those to make sure everything is mixing together." (I8)

On the subjects of consistency, there are indicators of a lack of consistency, i.e. 'sickness' that operators can look for, as an operator describes:

> "Don't overfeed it. If you feed it too much it'll start foaming. The bug will go crazy. The oxygen level needs to be correct and the pH level right. It's like feed it right, you won't have any problems. But once you start eating the wrong stuff or too much of it, you're going to get sick. The digester is the same way. Other than it's a mechanical digester, instead of a cow or human. If you treat it right, it'll treat you right." (I12)

Another operator spoke about this sickness indicator of foaming:

> "You'll have to watch the bubbles. You may have to change how to mix it. You may have to turn off the mixers for a couple days. Let the stomach settle down and then go

back to your normal operation...when the digester is healthy and the bugs are happy. At the discharge end of the digester, you can see the manure coming out. In between times when we pump manure from the barn, bubbles will form on top of the manure because it's not flowing. When your bubbles are nice and big, and kinda have a rainbow color to them, your bacteria is happy. When your bubbles are really tiny and tight and look more like brown foam, then your bugs are not so happy. The real brown foam usually [indicates] you have too much sugar in it or you're agitating it too much and you're pissing the bugs off. And if you have no bubbles, that's not good. That means you're not doing well...your gas production has fallen way off, your bacteria are very sick and are not doing what they're supposed to. So the bubbles coming out of the digester indicate how well it's working. You want to see nice big bubbles with a nice rainbow sheen to the bubble. When you see them, you know everything is working well. When they start to disappear, they'll start to go to a cloudy bubble, then a smaller bubble and then it starts to get smaller and look like foam" (I16)

If an operator foresees a challenge with feeding due to an inconsistency of feedstock, one operator mentioned adding "enzymes to help the digester capture some of the variables" (I20). This seems like a proactive way to prepare the microbiome of the digester for changes in feedstocks. The US systems may benefit from examining European ways of maintaining consistency:

"When we're talking about feedstock, in Europe, they're using corn silage. They're using prairie grasses, they're not using waste products. So it's a completely different ball-game...Why? Because it's consistent. It's a very consistent feedstock that you know what you'll get. You can test and you can say "this is the value and this is the silage" and you know how much to feed everyday." (I17)

It is unlikely that US systems will turn to agricultural products instead of wastes for feeding digesters, as this can further exacerbate food and feed distribution issues. What might be the best way of maintaining consistency is keeping simplicity and status quo, as one operator said:

> "We would not expand the digester [operation], and we would continue it status quo because we know how that works and we know how to keep it working. And if we expand it, odds are, we're going to change something and we're going to have to go through the learning curve all over again. Keep it going the way it's going and keep it simple. It's not an additional expense and not an additional headache" (I16)

Simplicity and consistency make for ease of AD feeding management.

Tipping fees are important in the decision making process of whether or not to take feedstocks, as the payment received should compensate the ability (or challenge) of the digester to handle it. One operator noted their tipping fee strategy:

> "The only way to make a digester profitable is the tipping fees, we've found. So you're going to have to take in the substrates to make it pay for itself...What the fee is depends on the quality, quantity, and consistency. If you're bringing me two loads a year, it's going to be a lot more than if you're bringing two loads a day. And if you're bringing me three thousands gallons [occasionally] it's probably going to be more than if you're bringing me 6000 gallons twice a day...Normally the higher the energy the more expensive it is….There is not much demand for high energy stuff. The other option is to run it through a water treatment plant. And most water treatment plants do not want to deal with your higher energy substrates." (I15)

One operator said, “Absolutely, you have to [collect tipping fees]” remarked that higher tipping fees discourage non-optimal or hard to handle materials (I9). This includes high liquid feedstocks (I4). Another operator highlighted the value of a potential depackager investment: “If you are getting straight food waste, it’s going to be a lower tipping fee than if it’s in a package” (I11).

In addition to tipping fees, carbon credits are another way of monetizing the material flowing into the digester. These credits though “are based on the cow waste, they are not based on any other waste” (I19). This may disincentivize feedstock acquisition. However, as mentioned previously, manure is a needed process to make even a feedstock acquiring digester work. How these carbon credits work is further explained by one operator:

> “Carbon credits. So the state of California and also some [provinces] in Canada have a program for companies that can never meet their ecological/environmental goals for wastes in terms of air pollution, they can take somebody like us, who is reducing or eliminating [wastes]. And that process creates credits and I can sell those credits to those companies. Probably who’ll end up buying it will be someone like Exxon, because they need to do a certain amount of credits to do business in the state of California...We don’t know who we’ll sell to until the end of the 2nd year collection period. So what happens when we get those, the state of California has a team that reviews the two years of what's going on in the digester: the manure that turned to gas, the gas that got burned, what didn’t get burned in the engine, and what got burned by the flare. So now that methane gas, from these cows at this facility, is going to go into the air. They’re going to review that, looking at every day for two years and looking at our monitoring. We have several meters that do different monitoring for H_2S and that type of thing. So they’re going to

look at all that. And based on that, they're going to assign us credits. Once we have those credits, we will have a brokerage firm find us a place to sell them to." (I19)

This subtheme has outlined lessons from the interviews regarding styles of feeding, what and how to feed digesters, and how tipping fees and carbon credits work.

2.4.3.5 PPAs, utilities and RECs

This subtheme was mentioned in seven of the twenty interviews. Electricity production is an important monetization strategy that is moderated by power purchase agreements (PPA). For any PPA to occur, however, the digester system, specifically the biogas combusting engine generator, must be tied to the grid. One operator described their connection, "We are tied to the utility. We are running three-phase. We are matched in phase, frequency and voltage" (I16). "Three-phase" is the term used by most operators to describe the level of connectivity required to input and sell electricity to the grid. Upgrading to three phase infrastructure can be quite expensive, depending on the policy environment regulating who has to pay for the upgrade.

Once hooked up, PPAs provide the negotiated payment plans for power. One operator wanted to describe their unique net metering PPA: remote net metering:

> "Net metering is where your electric meter will spin backwards. [Imagine] you're making power today and you're not using it all on site so it spins the meter backwards and then the electric provider will give us a negative electric bill if everything goes right. [With remote net metering] we sell the power to someone within our load zones. We're going 20 minutes west of us in the large city and selling to an extremely large modeling company, and they buy 80-90% of our power. And we give them a coupon stating that they bought it from us. And they turn that coupon in with their energy bill and then in

> turn they get credit for using renewable power. We sell it to them at a 10% discount and the world goes around that way. It works pretty good that way." (I4)

A standard net metering PPA is described by the excerpt:

> "We're going to use what we need and the rest gets sold. We can sell [electricity] at the rate that they sell it to us for. So that's what makes this work. If we had to wholesale it, we'd probably go broke." (I9)

Some imagine that digesters can make a farming operation energy 'independent'. This can occur as the case was with the operator of interview 16, but is relatively rare. When asked if the farm was energy independent, one operator answered:

> "I'm not sure what energy independence means. My power goes out on the grid. It hasn't made me energy independent. But I don't have an electric bill every month." (I15)

This exemplifies the standard way of renewable energy with digesters: sustainable energy production, which is not necessarily energy independent. Digesters are typically tied to the grid and when the grid goes down, so does the energy consumption and delivery capabilities.

Renewable energy credits are one way of monetizing renewable energy production with biogas. They are "based on the power that we are selling" (I19). After a certain period of time, these can be sold. Some of the credit deals can be of significant sums. One operator suggested having an experienced broker to manage the negotiation:

> "My word of caution, this may be a bit more difficult. Just like if you or I were selling any investment that may be in the $5 million range. It's nice to have somebody with some experience to help you out there." (I20)

2.4.3.6 Gas and engine management

Knowledge on gas handling and engine management was mentioned in eleven of the twenty interviews. The AD process produces raw biogas, which is primarily methane, carbon dioxide, and also hydrogen sulfide and water vapor. It was mentioned that gas productivity was highest in the summer and lowest in the winter (I2), and more is made "during the day than we do during the night" (I16), possibly referring to the seasonal and daily fluctuations of temperature. To turn the raw biogas into an engine friendly form, some will use chillers and scrubbers. A chiller will "cool the gas down to 55 degrees, [then the] water will condense and drop out of the gas" (I8). The debate over whether scrubbers should be used is more contentious. A scrubber, as one operator put it, is like:

> "A sponge...there's bacteria in the gas that breaks up the H_2S that we feed them if we give them the right environment. So we give them the right environment in a fiberglass silo and pump water through, and keep them moist and then they do a good job getting the H_2S out, but they excrete elemental sulfur, which plugs things up if you don't stay on top of it." (I13)

This maintenance and the up-front costs prevent many operators from adopting this technology. One operator explained their experience in deciding whether to get a scrubber:

> "We actually do not [have a scrubber]. We attempted to and we couldn't get things working. As we researched things, people I knew who were doing it, quit doing it because it was too expensive to maintain the units. So they thought it didn't pay to do it… The engine people claim that we need to change the oil more frequently and the gas is a bit more corrosive. They figure the maintenance cost is probably higher, but I'm not sure you can justify spending too much money to bring those numbers down." (I14)

One operator illustrated their experience pre- and post-scrubber with their engine:

> "The first gas engine was a naturally aspirated engine. There were no standards at the time for emission coming out of these engines. And we ran uncleaned gas into the engine and we managed our gas quality with our oil changes more or less. The more ash we had in the oil the longer we could run on an oil change. As we learned, we put a scrubber in to clean up the gas and we weren't able to run the same oil, we learned a lot about different oils and how they worked with different...with clean gas versus dirty gas." (I13)

It seems solid understanding and attention to the needs of the engine for oil changes may be the preventative measures required to take if a scrubber is not installed.

2.4.3.7 Digestate and bedding management

Knowledge on digestate and bedding management was described in eight of the twenty interviews. This section contains lessons and ideas on separation, effluent testing, spreading, and bedding. When the effluent leaves the digester it is voluminous and water-laden. For better usage and storage, operators will separate the liquid and solid portions using a variety of techniques. One operator describes their roller press technique:

> "We have a three-series roller with a dewatering column so we pump that digestate into our press which gets rid of most of the water. Then there's a 6 ft roller, a 4 ft roller, and a 2 ft roller, that they have to go through. They're stair steps, so gravity helps us out in that way. So what that does, is it separates, it's not 100%, it's about 85% or so...The liquid portion is squeezed out, drops into the tank below the press and that makes its way to the lagoon: the same 30 million gallon lagoon. So that's why we like to run the press, because it takes so many solids out of the lagoon because solids take up so much more space than liquids" (I8)

Another operator described their screw press technique and also their almost counterintuitive, yet ingenious, desire to not separate too much of the liquid out of the solid:

> "We separate our manure fibers with a screw press, we do not separate with a centrifuge. Some digesters separate with a centrifuge. You can collect more fiber with a centrifuge, but the difference is you're collecting more of the finer fiber. Once it's dried, we dry it down 15-16% so it's coming off the screw press at about 60-70% moisture and we draw it down to about 50-51%. Any dryer than that, it begins to be light and fluffy and lighter than air. And we really don't want it blowing around, getting on the cows and getting in their eyes and nostrils. So we only dry it as much as we mention, but it works well." (I20)

Too dry and the manure solids will become a welfare issue for the cattle, as mentioned above. This leads to the application of digested manure solids as bedding. The manure solids can be used and are relatively comparable to sand bedding, but:

> "Sand is always ideal for bedding cows. Sand is as good as people claim it is. There's no organic material for the bacteria to grow on, but it's hard on equipment. (I17)

One operator described that digested manure fibers require a different type of intensive management to make sure that the cows stay healthy:

> "A lot of guys will say that when they switch to organic fiber their somatic cell count, or the milk quality is better. It's better because they're also taking more time and more care of their beds than before with sand...They're managing the beds better because they know that there is a higher risk of mastitis because it's 100% organic material. So, guys will start comparing apples to oranges; they're bedding switched but they also switched their bedding practices along with it. So you've probably heard that some people have switched from sand to organic and their cows are so much better and their somatic cell

count went down. Well, I'm willing to challenge them and say 'how many man-hours are you putting towards your bedding compared to before?' Most of them, I'd probably say, are taking more time to clean out the stall, they rake them, and they take better care of them." (I17)

In summary, organic and digested manure fibers have a higher risk for propagating bacteria as compared with sand. This means increased management of the bedding, but may mean less damage to the machinery. Additionally, as sand is relatively incompatible with AD, the benefits of manure solids with AD may provide significant incentives for adoption.

For most operators, particularly the ones who separate, the liquid portion is spread on agricultural fields. Before spreading, many operators will test the effluent on a near-frequent basis to understand the nutrient value of the material that will go onto the fields (I7, I8, I14, I17, I20). One operator outlined their spreading schedule:

> "It was like 28 million gallons of manure we pumped out of our basin here on our home farm. So we pump as early in the spring as we can and take out as much manure onto our farmland as possible. Again pump following maybe for some nurse crops or alfalfa in late May or early June. Again, apply more manure after winter wheat has been harvested In the first part of August. Perhaps more manure after the third crop alfalfa. Third crop alfalfa would come off the third or fourth week of July. So we try to harvest about 28-30 some days, so that would be late May, late June, late July and late August. That gives us four crops of alfalfa grass silage in the upper Midwest." (I20)

Another operator described why they believe dragline spreading is better than fertigation:

> "During spring and fall basically, we apply the liquid to the land. Fertigation can be done, but the odor control is not the greatest...We just feel without secondary separation,

[which would] remove NPK from that digestate, the way we're doing it is a little better. When you remove NPK from the digestate, you get a tea water, if you will, a lighter browner water, that you can see through. Now you have removed a lot of odor and fertigating, or irrigating is definitely the best way to do it. But you have to have the secondary separation in place, to be able to do that...but ours is just a black digestate color. We don't currently remove extra NPK out of the liquid, as a secondary separation, where you have a centrifuge." (I6)

This operator describes another reason to limit the full capability of solid and liquid separation: leave some nutrients in the liquid for spreading on the fields. If one reduces the solids content low enough, they can spread through fertigation but this may lead to neighbor odor issues and reduced nutrient spreading on the fields.

2.4.3.8 Division of knowledge and responsibility

This final subtheme was mentioned in thirteen of the twenty interviews. As a subtheme, division of knowledge and responsibility pertains to how an operator does not need to know everything about the AD. An operator does not need to be the only one who supervises the AD or need the AD to be their only task. On any operation, there is a division of responsibility and know-how that when complemented by others, there is a synergism. One respondent shared a lesson about responsibility for the AD:

"It helps to have one person who manages the AD for consistency's sake, but other people who know enough to manage it when that person is not around" (I16).

One worker may know just "enough to keep that thing running" (I15), but even if they knew more, there seems to be a healthy level of humility in how much each operator thought they knew:

> “This particular facility has had issues...and you're going to ask me why and I’m going to tell you I don’t know. If I did, I’d be a rocket scientist.” (I4)

Another mentioned, even though they had 13 years of experience working with digesters, “it doesn’t mean I know everything” (I16). This healthy sense of not knowing seems to accord with the ever dynamic process of AD; if you stay alert and learning, the AD will teach you new things. It’s important also to note that these operators have many responsibilities, some more or less than others. One mentioned that others “do cows, I do topsoil, mulch and a bit of construction” (I9); and another mentioned their specific delegation to AD supervision:

> “I’m not 100% sure how many cows they actually milk. That’s not my department. They call this the energy center building here. I just stay up here and I monitor what goes into the digester and when, that kind of thing, and I actually do maintenance on the engines.” (I8)

Some operators actually have third party supervisors that will do most of the operation:

> “We don’t necessarily deal with the operation of the digester. That’s done by [the third party supervisors]. I’m there on the facility, we make changes, but a lot of those questions [they] could probably answer better” (I2)

Others have divided the responsibility and knowledge amongst the family:

> “If you could send an email, with those questions to my son, he could answer those. I could too, everything is available with the technology on the screen of run time, flare time, everything it's all there. Energy produced, gas produced. We got the info.” (I12)

There is a lot to know about AD, however, sharing responsibility and knowledge about AD is important.

2.4.4 Collaboration

A lesson that came out of the interviews was the importance of interdependence. The digester and the farm do not live separate from other systems, enterprises, communities, and people. Understanding what connections make AD successful should be a critical task of AD planning.

One important connection is to the federal, state. and local officials, as described in fourteen of the twenty interviews. This includes state departments of environmental protection/management, departments of agriculture, the USDA and EPA, university extension, treasury departments, township supervisors, state representatives, and even the state chemist. These entities oversee power purchase agreements, all kinds of permitting, incentives programs, and provide financial and public relations support.

Another important connection is to utility companies, as mentioned in fourteen of the twenty interviews. This interconnection is vital for creating an energy monetization strategy. The utility makes sure that “everything is connected, safe, and working properly” (I16), in addition to being a gateway for a profitable power purchase agreement.

The next important connection is feedstock suppliers and transporters, as mentioned in fifteen of the twenty interviews. These included supermarkets, restaurants, canning factories, biodiesel factories, cheese-making facilities, a yogurt plant, Walmart, a poultry processing plant, industrial chemical factories, and general food manufacturers. Several respondents mentioned having trucking/hauling connections that aided in their acquisition of feedstocks; one even part-owned a hauling company which allowed them to collect manures from neighboring farms (I5). If a digester is co-digesting feedstocks, the reliable connection to a feedstock supplier is imperative for consistent feeding of the digester and for improving biogas potential. As this connection can determine the success of appropriate feeding of the AD system, three of the twenty operators mentioned using third parties (middle people and brokers) to govern this connection.

To ensure the success of their AD, some operators looked towards third party consultants, and project aids to assist them, as mentioned in ten of the twenty interviews. These individuals and parties included those who could help with permitting, grant writing, brokering RECs, public relations, and the microbiology of the digester. They also were the engineering firms that helped with design, the contractors who build their systems, the generator companies, subcontractors, pump manufacturers, the manufacturers and suppliers for the AD parts, in addition to the crop consultants, commercial fertilizer applicators, extension agents, biologists and attorneys. There are so many responsibilities that come with AD, it may be helpful to look for external help that may be beyond the expertise of the already hired staff.

This external help has extended to some even having third party owners and operators, as seen in four of the twenty interviews. This allows others to initially invest and get the digester going, and allow the dairy producers to offer peripheral support for the AD and continue to focus on milking cows.

The next vital connection is with neighboring farmers and neighbors, as mentioned in seven and five interviews, respectively. Neighboring farmers primarily provide mutual support by incorporating their nutrient spreading plan with that of the AD; in other words, they will accept the digestate, separated or unseparated, so that the nutrients digested can appropriately go onto the right amount of acreage. Additionally, they'll buy bedding and offer consultation during construction of these AD systems. Non-farming neighbors commonly were referred to when discussing odor issues, but also they would buy digestate and be part of the community meetings that affect the on-goings of the farm.

One must not forget the financial institutions that help to front the costs of these expensive technologies, as mentioned by four of the twenty interviews. These can be banks and also non-profit organizations.

Finally, eight of the digester operators specifically mentioned the digester design companies that they worked with, including US biogas, Envitech, RCM digesters, and DVO digesters.

2.4.5 Uniqueness

This theme is a bit unconventional, as it required more than the other themes previous knowledge of AD systems and a meta-analysis of all the interviews. The theme of uniqueness stems from a series of excerpts that revolve around the understanding that "there is no one way to do [AD]" (I7). Another said, "[AD] is like a snowflake, no two are the same" (I16). Awareness of uniqueness was mentioned several times in different realms. Some of the differences can be due to differences in state by state regulatory/economic environments:

> "Every situation is different; whether you are in CA, if you're west coast it's different than if you're east coast. Or if you're Midwest, whether that's northern Midwest, southern Midwest, there's a lot of variables within that." (I17)

Other differences can be due to personnel:

> "It's like any business model, or any other industry. There are people who pay attention to the minute stuff to make it work, and there are others that don't and it's all management." (I7)

The following are some of the unique differences between digesters in several realms: third party involvement, digester designs, feedstocks, gas and energy utilization, and digestate utilization.

2.4.5.1 Third party involvement

There are four digester operations worthy of distinction in their unique approach to third party involvement. The operator in Interview 1 arranged their system to have solids separation prior to the digester, allowing for a stream of pre-digested solids for third party involvement. In this situation, they have a third party that will take the solids for free, and will compost it for sales to local farmers. This takes the role of composting, drying and curing of solids out of the responsibility of the AD operator.

The AD operators in Interview 2 had third party operators who managed the digester enterprise and its energy generation. This third party oversaw a "cluster of digesters" regionally, handling the daily operation, leaving the farmers and owners of AD to peripherally supervise the AD and handle the material flow to and from the digester. Another owner/operator explained their similar operating system:

> "[We are a] single farm operation run by a managing group that manages for us. So it's not farm run. We have a professional operator, a paid employee, we're more of a cooperative because there's five farms that work together to run five individual digesters with one common goal…[to] make a shitload of power" (I4)

Similar, but different, the operator in Interview 20 described how they had a third party investor invest in the digester at first. This arrangement made sure that the third party investors/operators could make sure that the digester was running and ready. Then the digester was bought out by the farm once the operation was steady. Eventually, this operator hired back the third party to operate the digester, which was now owned primarily by the farm.

These unique third party cooperations offer promise for shared responsibility and risk in making the massive investment of AD, especially for farm operators who would like their primary responsibility to stay dairy focused.

2.4.5.2 Digester designs

Not all digester designs are equal. Some work better than others for specific operational goals, needs and environments. For example, the digesters that were covered lagoons worked especially well in California because of their ambient warm temperatures.

Previously described were the main types of digesters: covered lagoon, complete mix and plug flow. But not mentioned were some of the less common variants, which a couple of our interviewed operators had. One operator had a vertical plug flow digester, in comparison to what most plug flows are: horizontal. They explained its design:

> "It's about a 160,000 gallon tank, upright with a roof on a closed top, enclosed tank. So it's an upright tank so it doesn't take a lot of room. It's about 30 ft diameter and roughly 35 feet high. The idea of it is that the heating and everything is external. So if something malfunctions or needs to be replaced, it's not inside the tank. Everything is outside the tank...There's some agitation to keep it stirring, but the pump and pipe is external. It's set every 20 minutes to pump material in to the bottom of the tank and the older material gravity flows out of the top." (I14)

So, in addition to the plug flow working vertically instead of horizontally, this digester has most of its mechanics on the outside for better ease of access. It also has agitation like a complete mix would have.

Another unique digester, a hybrid complete mix/plug flow digester was described another operator:

> "Our [digester] is a hybrid. It's not a complete mix. It's not a plug flow. It's kind of a hybrid mixed plug flow digester. When ours was built it was one of the first they built that way. It was, instead of your standard long rectangular plug flow digester at the time, it is a round tank with a divider wall in the middle. So the round tank is a heck of a lot easier to construct than a rectangular tank. So, you change how much the mixers run, because they run on a timer" (I16)

The digester model is not fixed and can be adapted to the needs of the operation, the materials and the construction crew available.

A couple of the digester operators were operating multiple digesters (I11, I17). For example, one operator was managing a complete mix and a plug flow (I17).

Another interesting uniqueness was the size differences between operations. One operator was handling the waste of 16,000 dairy cattle through their digester (I3). Another operator was handling the waste of 475 dairy cattle (I4). Both were operating complete mix digesters.

Most commonly digester operators had their cows in free stall barns. Free stall barns themselves have unique ways of moving manure away from the cows and towards the digester. Two of the operations had different cattle housing arrangements, which had unique ways of manure management. One operator housed their cattle in stanchion tie stall barns (I5), and another operator had their cows all on dry lot yards (I3).

2.4.5.3 Feedstocks

A great deal of variety came from the ways people fed their digester systems. Different operations have different styles of feeding and different access to feedstocks. To illustrate, there were two conflicting styles of feedstock acquisition that inevitably had effects on feeding. One style known by many as “chasing tipping fees” (I7) or what can be known as ‘take what you can get’. One operator exemplified this style, describing their motives and limitations as:

> “Your money making is your tipping fees, so you’re going to want to bring in as much as you can within your limits. You’re limited in the amount of gallon you can bring in annually.” (I17)

Another operator had an antithetical style of feedstock acquisition, which is founded in their understanding of the previous style:

> “The digesters who chase high tip fees end up running a high potential of upsetting the digester and create more effluent which means you need more acres” (I7)

So to minimize the biological upsets, the above operator does not attempt to acquire as many feedstocks as possible, but instead focuses on producing as much biogas as needed to “run the engine at 100% time and 100% load” (I7). They aim to acquire high methane potential feedstocks including “fats, oils and greases” (I7). This style may have lower tipping fees, but may have the highest capacity for electricity production in relation to total capacity of their engines.

What the digesters are fed varies greatly among the interviewed operators. Some only accept onsite organic wastes. This may mean only manure (I2, I3, I10). But one of these accepted wastes that are technically considered on-site, but are actually three satellite dairy farms, leading to having a tremendous amount more of wastes input into the digester (I3). Accepting only onsite wastes may mean codigestion with a co-located food manufacturing plant. One respondent of this type had a dairy with a co-located cheese processing facility, allowing the digester to receive both cheese plant wastes and manure/waste water from the dairy (I1).

Some operators will accept off-site organic wastes. One operator had a trucking company that "hauls manure from smaller acreage farms," in their area and feeds it to their digester (I5). This style is very similar to a centralized digester system. Most other respondents, if they are going to expand their operations to include off-site organic waste acquisition, will most likely search for non-manure based feedstocks. These organic wastes could be "french fry oil to grocery store wastes to ice cream, it could be anything" (I4), including "industrial byproducts like glycerine bottoms from biodiesel production" (I8), even non-traditional feedstocks like "tide laundry detergent" and "rendering works" (I20). One operator mentioned taking packaged goods like sodas, which could be used with their depackager and increase their tipping fees, saying "If you are getting straight food waste, it's going to be a lower tipping fee than if it's in a package" (I11). Another operator mentioned that their feedstock acquisition was so great that they were mixing about 50-70% food wastes with manure (I9).

There was one operator who had a license to accept feedstocks, but chose not to (I15). Another mentioned not asking for tipping fees for feedstocks (I18).

2.4.5.4 Gas and energy utilization

The uniqueness of this theme comes from the unique biogas usages, scrubbing, and power purchase agreements (PPAs). The biogas use of most intrigue came from one respondent that had a trigeneration system, where they produce electricity, heat and chilled glycol for cooled water. They explained:

> "It's a heat driven chiller system, so it's an absorption chiller, ammonia-based heat absorption chiller...Every engine, whether it's in your car, or tractor, they all have cooling radiators. So, with that radiator, we're running that through an absorption chiller, an ammonia." (I1)

This additional route of biogas usage could be revolutionary for the digester industry. However, this was the only digester system to do trigeneration. Others were primarily doing co-generation: heat and electricity.

Another unique operation had a radio controlled breaker that allowed the digester to run off-grid, particularly if the power goes down. They describe:

> "I've heard that some people are tied to the utility, so when the utility goes out, they can't run their engines....Nope we can. The way we set things up, now it cost us an extra $15,000 to do that. But we have a radio controlled breaker, so that when the utility goes out, it communicates with the generator and we break ties from the utility and we keep on running the farm." (I16)

There is variation in whether operations have buy-all-sell-all, net metering (or even remote net metering). This was relatively evenly distributed among the respondents. Additionally, there was evenly distributed variation as to whether operators chose to invest in scrubbers to clean the gas.

One unique experience of one operator was their advocacy for digesters in that they helped to initiate the Sustainably Priced Energy Enterprise Development (SPEED) program in Vermont, which is viewed very favorably by digester operators around the country. They explained:

> "We ended up going to the government, the legislative body, and back then green energy was all the rage. We said, "look if you guys are going to go around and encouraging this sort of thing, then how about incentivising it?" So we ended up working with the utility and with the legislative body to come up with the SPEED program." (I18)

The SPEED program is a model for digester-friendly development.

2.4.5.5 Digestate utilization and sales

The handling of digestate additionally offers a source of variation among AD systems. There were five operations that did no solid/liquid separation (I4, I7, I9, I11, I17). This means that they were not using the solids as bedding for their animals, using the digestate instead for spreading purposes only. Of respondents separating solids, there was one digester that separated and sold their solids pre-digested (I1). The other respondents were separating their solids post-digestion. Within the group of post-digestion separators, there were many ways of separating and drying. One operator separated their solids with a roller press:

> "We have a three series roller with a dewatering column. So we pump that digestate into our press which gets rid of most of the water. Then there's a 6 ft roller, a 4 ft roller, and a 2 ft roller, that they have to go through. They're stair steps, so gravity helps us out in that way. So what that does is it separates, it's not 100%, it's about 85% or so...the liquid portion is squeezed out, drops into the tank below the press and that makes its way to the lagoon: the same 30 million gallon lagoon. So that's why we like to run the press, because it takes so many solids out of the lagoon because solids take up so much more space than liquids" (I8)

One operator separated their solids with a screw press:

> "We separate our manure fibers with a screw press, we do not separate with a centrifuge, some digesters separate with a centrifuge. You can collect more fiber with a centrifuge, but the difference is you're collecting more of the finer fiber. Once it's dried, we dry it down 15-16% so it's coming off the screw press at about 60-70% moisture and we draw it down to about 50-51%. Any dryer than that, it begins to be light and fluffy and lighter

> than air. And we really don't want it blowing around, getting on the cows and getting in their eyes and nostrils. So we only dry it as much as we mention, but it works well." (I20)

Another operator separated their solids through non mechanical means using a series of overflow lagoons:

> "So by the time you get into the last one there's next to no solids because it's back in the liquid lagoons. So from the last stage, they'll irrigate through center pivots onto the crops. And then the ones further up, they'll drag line or haul into the field and spread normally in the fall. Almost always in the fall." (I17)

This method prevents usage of the solids for bedding. There are also drying steps. One operator described using a drying floor:

> "That utilizes a fan blowing holes and piping that blows warm air through. Some of the heat goes through a radiator, so some of the air that goes through the material is warm and dry to help dry it out." (I14)

Another operation could uniquely use their biogas to fuel the dryer, otherwise it could use liquefied petroleum gas (LPS) (I20).

Lastly, one operation had troubles with udder health using manure solids uniquely leading them to switch from manure solids to sand (I13). Usually seen is the opposite transition; once getting the digester, an operation will usually move from sand to manure solids.

2.4.6 Future

The operators in all twenty interviews had visions for the future. They understood the challenges that they faced and could envision a pathway that would be easier for themselves, for new adopters of AD technology, and for the field as a whole. These wishes and predictions for the future could be categorized into permitting and finance, nutrient management, renewable natural gas, and science and technology upgrades.

2.4.6.1 Permitting and finance

This subtheme, the future of permitting and finance, was mentioned in thirteen of the twenty interviews. A frequent idea expressed was a desire for policy makers to know more about AD so that reasonable policy pathways can be put in place for easier AD adoption. This comes from a sense that policy makers are not staying up to date of the technology evolution related to their renewable energy policies.

> "I'd have to say most of the time the people who are making the rules and regulations don't always have first hand experience on how [their policies] are going to affect." (I17)

One respondent mentioned that they'd like "regulators who are willing to stay engaged and really step up on [AD]" (I20). They elaborated on the challenge a non-informed policy influencer can have on AD regulations:

> "So, for instance, you can have an idiot...alright, I'm going to speak bluntly...You have an idiot or two on your town board that can make this burdensome or impossible, so maybe you need the folks with the knowledge and some fortitude to stand out and really call them out on it. Really let it be know what is true and what isn't. But if you've had a relationship between a county or state agency and they tire or don't care to invest or don't have the resources to invest with engaging with that town board, who's going to end up winning at the end of the day the science or the community or the digester, or one or two stooges on the town board." (I20)

With a greater awareness of AD, there is hope that the commitment of society and the regulators to renewable energy may include AD:

> "If somehow the regulatory bodies, or government or the nation, whatever, if we're going to make a commitment to renewables, we have to make that commitment of all renewables." (I7)

A commitment to AD includes creating monetization strategies and permitting pathways that make AD possible. This includes incentivisation:

> "Incentivize the process. In other words the government has money to fund the countries that don't even really like the US. why don't they fund some agricultural interests to put digesters on the farm? Get involved in the political process, make it work." (I18)

It includes overseeing the financial arrangement and willingness of the utilities to work with AD:

> "To me public policy doesn't have a whole lot to do with it, other than working with some of the public utilities that have policies in place that cause installation to be more expensive." (I16)

Additionally, the commitment could include the installation of voluntary rate programs that allow people to pay more for electricity if they would like to:

> "A public policy suggestion that I would say, 'would you be willing to pay 2 cents more per KW if it is green?'. I don't think that there should be tax dollars, I think it should be a personal choice. Like how you go into the grocery store and buy green things. Power ought to be the same thing...That's the kind of public policy that I think should be introduced, but I don't know if it'll ever be introduced… At least [let's] make a pitch to the people and say 'you get power for X, and green for a little more'. It's a personal choice." (I12)

Vermont has a very similar program, the Cow Power Program. They also have the SPEED program, which one operator touched on:

> "In Vermont, they're paying 15-20 cents per KW and I think you'd see more anaerobic digestion if you'd see more being paid for electricity they made" (I13)

Another operator echoed this statement:

> "So in some states, I know like VT, they have an enhanced rate for the value of the power that a guy could generate. In [our state] that's not the case. So If they're trying to influence policy or provide policy that would influence the use of digesters, the enhanced electric rate would make it more likely economically." (I10)

The success of AD is about money. Those interested in adopting the technology should be relatively sure that AD is a sustainable investment:

> "[AD] is a lifetime process and somehow we just need to get enough revenue into the digester system, just as much as we need, and reasonable enough milk prices to make it a lifetime proposition. Not hanging on for 1 or 2 years or every 5 or 8... It's really imperative too that we take a step back and look at the financial model and the biological model, are we comfortable with this? Will it pay or be close to paying?" (I20)

Making it pay is important. And making it simple permitting-wise to adopt, as well:

> "You gotta have a permitting pathway that is reasonable, in other words, it can't be a year and a half process or people just don't want to deal with it. It needs to be a very streamline permitting process." (I1)

Other operators added their thoughts on permitting solutions to the challenges they face. One being the challenge of getting feedstocks tested and approved; they suggest it should be the generators responsibility, so that testing would happen once instead of many times by all the feedstock accepting AD operators:

> "Testing and approval of that testing product and what happens to it should be the generator's responsibility. Meaning that if I'm generating the waste, I should be getting it approved for disposal at the various ways I can dispose of it because I'm producing it, instead of pushing it onto us, the digester or the land user... All that needs to be regulated, but it seems to me that it just makes more sense to have feedstock approved. For example, I've got a feedstock producer that produces a lot of starch, excess starch that they've got to get rid of. If they produced a whole load of starch that's going to go to 10 digesters and they're all in [our state], all 10 will have to get that approved. That is my example. That's one thing I think that public policy is half-ass backwards." (I7)

This would streamline the permitting process for feedstocks.

Another operator suggested a permit for having the effluent lagoon post-digester covered for surplus biogas production. They explain:

> "Our effluent pit is actually open to the air. I know that not all the methane gets out of the digestate before it gets out to the pit. So I think it would be beneficial if we covered that [pit] and continued to collect the gas that comes off. When it's cool in the morning, I can definitely see that there is gas coming off of it. I know it's in part because of the temperature difference, but I'm sure there's some methane in there. I think that would be beneficial if there was some sort of permit that would state that you have to cover the effluent pit." (I8)

By covering the effluent pit, extra collection of biogas may be possible and it could also prevent rainwater from filling the pit and preventing storage issues.

Another suggestion for improved monetization would be opening up the Renewable Identification Number (RIN) systems to include electricity produced from biogas for vehicle use.

The RIN system is designated for liquid biofuel in a similar way to the REC system is for renewable electricity generation. One operator explained:

> "A specific policy recommendation I'd give to better our lives is to activate the electricity RIN pathway to allow biogas made into electricity to qualify for RINs through the renewable fuel standard. Currently the upgraded biogas is able to be qualified for RINs, as they ultimately go into a compressed natural gas state into a transmission vehicle. But if that were to go into a personal vehicle today, no matter where it goes, it does not qualify. So, activating that pathway through that program would boost our returns from a renewable energy standpoint." (I11)

This recommendation may be a challenge as it would require a redefinition of the EPA's Renewable Fuel Standard to include biofuels used ultimately for electricity production.

Lastly, one operator felt frustrated by the regulations imposed on the post-digested separated liquids. These liquids can be thoroughly filtered, and the technology does exist to purify the water enough for safe injection into a stream. But technology has not had much effect on regulation:

> "In [our] state...they treat digestate and manure from a farm no matter what state it's in, whether it's filtered water or thickened manure, it's the same product. So the environmental regulations around that are pretty stringent. But simply if you run the digestate through a membrane and separate the water from thickened manure, you still have to environmentally treat that filtered water the same way [i.e.] put that water into a holding pond, apply it as typical manure. [That is] because policy hasn't recognized technology yet. So, the adoption of technologies ready to do that is going to be contingent on environmental policy catching up with the technology." (I11)

Policies on AD should lead the industry in a societally beneficial way. Often though, it seems that they may limit the possibilities of success. It may be because these regulations are made to limit, instead of promote, as mentioned here:

> "It's like every industry, there are people who abuse the system who create bad things that happen that create the regulations for the rest of us" (I7)

2.4.6.2 Nutrient management

A major challenge that was mentioned by the operators in six of the twenty interviews was nutrient management. One operator explained:

> "Our biggest problem is dealing with the digestate. Because the farm has X amount of manure and we bring in twice that to make more power. The farm has challenges to get rid of all that product on our fields. If there was one thing that if we could solve with our crystal ball that'd be it." (I4)

What do you do with all that is left over post-digester? One operator added their thoughts on trying to evaporate the liquid volume:

> "How to get rid of it without having to do anything! Put it in and it goes away….[So that] it disappears. I mean it's just not cost effective. We can evaporate our digestate, but that's a tremendous amount of heat, equipment and investment to do that. You're basically doing what an ethanol plant does...They produce so much liquid product from the mash being made into alcohol that they have to dry it back down. They run evaporators. And it's just the amount of gallons that they're producing is smaller than the amount of gallons that we're producing and it's amazing. The tremendous amount of power, electricity, that goes into evaporation. It's not very cost effective. Especially if you don't have a market for the fertilizer that you're trying to produce.

Instead, the possibility of discharging residual water into a stream would offer a solution:

> "One thing that would be helpful along those lines is that if you're able to find the value of that digestate by separating it into components you'll be left with water. And in our part of the world, water is not as valuable and our ability to discharge that into a navigable or intermittent stream would be extremely valuable because we wouldn't need to handle all that volume on an annual basis. So the other day, we're producing a lot of digestate, a lot of that is water, and we need to figure out how to get rid of that in a cost effective way. That would be a huge win." (I11)

But this process is highly regulated and limited in its possibility because of policy, as described by one operator:

> "Can we take the manure coming off the digester, after we've squeezed the fiber, clean it up to higher quality and discharge that water into a stream? Yes absolutely it can be done. Has it been done on an experimental basis, on a large scale? Absolutely, very successfully. Can it be done economically enough to justify? Very close to it. Is it done? Not really, because it's so hard to get that permit to discharge into a stream. Could I irrigate it out onto the fields? Yeah. but then it's not worth separating out. I can put my nutrients out on the fields. But, if we can reduce that volume of water in our post-digester manure basin, that would have a huge impact on the amount of nutrients that we have to pump out through our hoses and to trucks to transport around the neighborhood before applying it to the field." (I20)

What the permitting process might take would be the water purification steps of a wastewater treatment plant called nitrification/denitrification, as explained by one operator:

> “We still have to get the nitrogen out of the water. We have a nitrogen problem in our drinking water...It all depends on the methodology of denitrification. Typically, in a municipal system, you would do a process called nitrification/denitrification, where [the effluent would] come out of the anaerobic digester and you run it through an aerating/aerobic stage. And with aerators, you make appropriate carbonated air for the bugs to take care of nitrogen. And then you move it back to an anaerobic pond, it does not need to be a covered pond, just not an aerated pond. Two stage process, nitrification/denitrification.” (I1)

This process may allow the nitrogen to be taken out of the water, lowering the COD/BOD to safe levels for stream injection. This process is extensive. If there was some way else to get rid of the water volume, there would be a chance for the solid portion being used differently. One operator described their challenge, the profitable dream of creating a marketable digestate and the challenges that the current system creates:

> “We’re still struggling with the back side, with the digestate coming out. That we need to remove as much nutrient, not so much nitrogen, but [remove] the phosphorus and potassium out of the material and make it cost effective and marketable for the farming community. Get it into a form that’s marketable, more than just for this market so you could ship it to others. And you could get it to other parts of the country to use it for fertilizer...It’s a very useful form of nutrient. Like rock phosphate has issues with absorbability. But these digestate forms are very available at a much higher availability of nutrients, but you have the issue of transportability because it’s expensive. We need to work on that. The issue that you have is that many dairying areas are very small areas. They do have to have a lot of crop production to support...We have 550,000 head of dairy

cattle right here in this valley. We have a very concentrated number of cows. We are starting to get over nutrient especially in phosphate, and we need to get that out of here." (I3)

The promise of a shippable form of dried digestate is commendable because it is comparable to commercial fertilizers, offering itself as an alternative:

> "The demand's there….Look at the companies involved in agricultural fertilizers. They don't want farmers to figure out that there's a better alternative to commercial fertilizers. You know, it's just like big oil. I'm not saying that it's drastically better, but there are other alternatives that can provide farmers with fertilizer that are not commercialized...Farmers around us love it. It cut's their commercial fertilizer bill and provides more than a commercial fertilizer can because you can get the organic matter." (I6)

If there was an easy way to monetize and distribute dried digestate, it would be a major advance for the industry.

2.4.6.3 Renewable natural gas

The future possibility of the industry turning to renewable natural gas (RNG, a compressed natural gas (CNG) equivalent) was mentioned in thirteen of the twenty interviews. There is a growing sentiment that "the future of making compressed gas is what [AD] is going to be" (I9).

> "The biggest issue that we've seen is certain policies have fallen out of favor. Such as power credits; instead of electric credits, now they're gas credits." (I3)

Operators are realizing that

> "The best return is not to run this through a piston driven engine and generate electricity. The industry knows that running piston driven engines to make electricity is not the way to do it. It's not as efficient as a gas turbine or huge steam plants [with RNG], but on a small scale, this is what's available." (I9)

Another operator explained where the value from RNG is coming from:

> "It's way more lucrative, just talking to the few people who are doing it. I think if we're comparing KW to KW, I think they're getting paid more like 48 cents per KW as compared to our 16 cents, which we think is great. They're doing better than we are." (I19)

The problem is the feasibility of adopting the technology for upgrading the gas to pipeline quality RNG. It very expensive:

> "So [those in WI and new projects] are looking for alternative ways to monetize the product, the biogas. At the moment, the best option for monetizing the biogas is to clean it up and put it into the pipeline. And then, sell the low carbon fuel standard credits with that. The downside with biogas cleaning up and pipeline injection, is that it costs a lot of money for gas cleanup for pipeline quality. Its extremely expensive. So essentially, it costs as much to do the clean up as the gas is worth. So they're not making any money on the sale of the gas, they're making money on the low carbon fuel standard credits. So the LCFS credits, at the moment, are extremely valuable. We'll see how this plays out in the next 10 years. We'll see if they maintain their value. There's probably 30 digester projects going up in CA in the next 10 years. So, we'll see what happens when those projects come online. And they are all participating in that LCFS market. At this moment

> that's how everybody is monetizing their digesters, or planning on monetizing their digester." (I1)

Another digester operator reiterated this point:

> "It's a significant investment. Just to give you an example, our CHP, our gen-set, would have been probably ⅓ of the cost of the new gas upgrade system. It's 3x the costs of the gas upgrade system vs energy generation through electricity." (I11)

One can hope that the credits, LCFS credits, that are promoting the shift to RNG stay profitable especially with more digesters upgrading. One operator envisions the future with RNG and hopes to invest in a fully RNG fleet of farm vehicles and machinery to create an energy independent system:

> "If you want to talk about energy independence, that's the way you want to go…[Start] buying equipment that runs on CNG, whether that's trucks, cars, or little tractors. So then the cows will produce your own fuel...Can anyone afford that? Hell no, that's expensive. Maybe we'll have one of those crazy fuel spikes when gas goes to $5 a gallon and then everything looks appetizing again. Right now, it's $2 million and, can you do it? Well, it may pan out on paper, it may not." (I9)

RNG offers a profitable possibility to the industry. With hope, the financial pathways continue strong and demand continues.

2.4.6.4 Science and technology

The last subtheme of the theme future, a mixed topic group, describes science and technology upgrades that would be helpful to the operators interviewed. This subtheme was mentioned in eight of the twenty interviews. The first future insight of a technology upgrade was pairing a greenhouse to the digester, which some have called digeponics: "One of the attractions is a digester with a greenhouse, then you can capture the CO2 out of the biogas and use the heat to heat the greenhouse and go that route." (I6). This sub-enterprise could offer vertical integration possibilities to a digester.

Another operator mentioned their interest in a depackager, which would allow them to receive a different and more lucrative stream of feedstocks:

> "[A depackager] opens up a whole other gambit that we can use...So if you had a contaminated load of Mott's Applesauce in those little dixie cups that they sell, and there was a trailer load, we would take it per ton. $60-70 per ton, instead of the dump, which they can't do in our area, they have to dispose of it right. We would take that, put it through the depackager, take the plastic and recycle and throw the apple sauce into the digester. It's a whole other way to make money and increase your food waste stream. Hopefully it pays off, that's the second gamble we're making." (I9)

There were two operators who discussed "how to do smaller scale, economical [AD] systems that are less complicated, that can be used on smaller farms" (I14). This comes from a problem described by one operator:

> "I think my biggest challenge with the digester is that we milk 500 cows, about 550, which is a pretty small size to operate a digester. So I know a few other guys who have digesters and they have more in the 1000 cow range. So they have the labor to commit a more higher skilled employee to maintain and operate a digester. We just don't have enough employees to do that. So I think that if it wasn't so complicated, it didn't take so much maintenance, it would make it easier for a smaller farm to do...Lower management hopefully for a smaller [AD]." (I15)

A smaller scale commercially available digester that required less staffing could possibly increase the reach of the industry to the large proportion of smaller farms.

Two operators discussed the desire to have better ways to get the H_2S out of the gas, specifically to lessen engine problems (I13). One operator discussed two new developments of gas purification, carbon ceilings and water bath scrubbers:

> "The European digesters have an attribute over the plug flow digester. They have carbon in the ceiling of the digesters and the sulfur is attracted to the carbon. The sulfur in the gas attaches itself to the wood and as it grows, as more attaches to it, it'll simply fall into the waste stream…[A nearby digester] has a water bath scrubber, like a shower, with a tank in media in it. It just showers water down over it, and the gas just comes up clean so the parts per million of sulfur dioxide in our digester will run from 1500 to 2200 ppm. If you get one of these gas scrubbers you can get it down to under 100ppm." (I18)

One operator illustrated their specific challenge and wished for some way to prevent roller press struvite buildup:

> "I wish we could figure something about that out, maybe not necessarily a chemical, some sort of material that can take care of that. We use, after we pull the post out, which is a big pain, we pour muriatic acid on it, and that tends to help loosen it to where we can chisel it off. But of course we aren't just going to dump a bunch of gallons of muriatic acid in the digester to fix that. It would have to be something that the digester could take well and could eliminate that. It clogs pipes." (I8)

The last group of operators described the desire for better service and scientific and industry development. One operator suggested a "Digester for Dummies" handbook that would list what one needs to do to successfully adopt AD:

> "There's a lot that you get hit with after you've started [AD]; did you get an environmental study on your air permit? Did you do this, or that? All the stuff comes out in the process...You know, it's kinda like getting your license, go study the handbook, go do this, go take drivers ed, you know what I mean? We have all those steps for everything else that people do." (I9)

This could be run by a county service or even a third party that oversees the adoption process. Another operator requested more standardization among digester systems, so then a third party could better oversee and offer support to AD systems:

> "It would be nice if there was some standardization or a third party who is willing to look at all of these systems and keep them working...They would have to be the group that would have mechanics available and would know each type of system. I think there are three or four out there. You could contact the DVO, they'd give you a rundown...or the DVO website. So somebody who knows how the whole system works and who could send a mechanic out to fix whatever piece of equipment that's broke." (I19)

There are a lot of mechanical and biological issues that would be better served if there was a hotline for support. Lastly, one operator discussed their desire for a deeper connection and knowledge of the AD industry network:

> "We know there are some folks, on the academic side, looking into this. There are professors and microbiologists with incredible knowledge of bacteriology. Kinda getting the word out, figuring out who's who in the industry." (I20)

2.5 Discussion

A main focus of this research was to highlight the importance of management for success with anaerobic digestion systems. From this research, it can be concluded that anaerobic digestion is a management intensive technology. It involves the management of both the mechanical and biological processes of the tank infrastructure, and also the management of incoming and outgoing material streams, the monetization strategies, permitting and regulation, staffing, neighbors' expectations, among others.

To stress the importance of management in AD systems, a reconceptualization must be made utilizing an analogy made by many: AD is like a cow, (rather than a machine or vehicle). On adoption of a vehicle, one schedules the routine mechanical maintenance, attends to the mechanical needs like engine fluids and fuel, and when one is finished operating the machine, it sits off, and waits until the next use. When describing AD as a renewable energy "technology", a mechanistic conceptualization may be instilled, which is somewhat incomplete. AD, however, like a cow, is living, and requires biological upkeep and continuous management. One needs to feed and hydrate it, keep it warm, and maintain its biological health, which often means attending to infrequent upsets, which can happen 24/7/365. Similarly, there is also a considerable waste stream that needs attention. Both cows and AD are part of an organic material stream, involving the input of feed and feedstocks, and the output of manure and effluent/digestate for cows and AD, respectively. Reconceptualizing AD as a biological enterprise helps to weigh the importance of management and frame the following lessons learned from the AD operators.

To aid in the outlining of management needed for AD, a summation of ideas and themes expressed by the operators will be expanded on in the following discussion. The hope is that these concepts are highlighted in order of importance and in a way that is helpful, especially for the new adopter of AD technology. This is of paramount importance as the field is both in its infancy and growing into its potential and, resultantly, there will be increasing new adopters as the industry burgeons.

Mentioned in 18/20 interviews was the idea of learning. This is primarily important because the AD industry is generally underdeveloped in the US, and as long as it is, AD operators will have to grow, innovate, and pioneer, as mentioned in 12/20 interviews, their way through the industry. To make matters more complicated, AD systems are unique to their environment; they're like "snowflakes, no two are the same" (I16). Different AD systems have different feedstocks at their disposal, different feeding strategies and goals for management, as well as different regulatory environments and monetary possibilities, among others. Thus each operator must learn individually the system they are a part of. This can happen by trial and error, observing what works and what does not, and, importantly, having an operator with curiosity and enthusiasm for learning. While each system is unique in some ways, it is important to realize the commonalities between digester systems and appreciate the learning resources available to the industry. One example is the AgStar program, collaboratively created by the EPA and USDA to promote "the use of biogas recovery systems to reduce methane emissions from livestock waste" and to assist "those who enable, purchase, or implement anaerobic digesters" on technical, business, policy issues, and feasibility of project implementation (EPA 2021b). There is also The American Biogas Council (ABC), a non-profit trade association "representing the entire US biogas industry" and dedicated to "maximizing the production and use of biogas from organic waste" (American biogas Council, 2021). To improve the learning process for AD, the ABC has multiple training courses designed for improving AD enterprises. There are also publications like BioCycle, a print and e-magazine designed to be a resource on "composting, organics recycling, anaerobic digestion and biogas" (Bioycle, 2021). There are also academic institutions that specialize in the development of AD technology, particularly Michigan State University's Anaerobic Digestion Research and Education Center and the University of Wisconsin Oshkosh biogas systems. Anaerobic digester design companies like Martin Energy Group, DVO Renewables, Northern Biogas, among others, will provide consultation and construction services. There are also opportunities for learning from the network of AD operators, domestic and abroad. Using the AD directory found on the AgStar site is a simple way to connect with other operators learning and implementing AD systems. The possibilities for education and individual investigation are bountiful and necessary for the growth of the industry.

A challenge to learning is tension between prioritizing the dairy and the ability of the dairy operators to extend themselves into managing the AD. As the operator in I2 described, the dairy ultimately comes first, and as the operator described in I19, the income from the AD consists of hardly 5% of the total income of the dairy business. While owners rightly should prioritize the dairy, "you have to have someone who pays attention to the details that keep it running" or else its mismanagement can lead to "not getting a return on investment" (I16). To run AD effectively, in other words, one needs help in both attending to its management and learning. A solution to this is staffing (mentioned in 8/20 interviews), third party operators (4/20), third party consultants (10/20), generally increased division of knowledge/responsibility (13/20), and even automation (6/20). AD is a management intensive technology and thus having the responsibility of learning the system and executing falling on several dedicated shoulders offers an advantage to the adoption and sustainability of AD systems.

When first conceptualizing the AD project, it's important to acknowledge what are the benefits that one can gain from an AD system. In order of times mentioned, from this research the top three most important motivators/benefits to the producers are 1) improved nutrient management (18/20 interviews), 2) odor control (14/20), 3) favorable power purchase agreements (13/20), power production (13/20), digester friendly regulatory environments (13/20). Noteworthy, is that while AD is often considered a renewable energy technology, as noted by the operators themselves, the major benefit is nutrient management, proverbially by "taking the manure headache away" (I7), and by creating a superior fertilizer, i.e. digestate, for pumping and for its nutrient value. This must not be underestimated. The nutrient value of the digestate applied is near analogous to the synthetic fertilizers produced by fossil fuels. Needless to say, the organic and inorganic content of the digestate depends and is highly variable on the materials entering the digester (Nkoa, 2014). As one operator mentioned, the buffering capacity of the digestate as a soil amendment is an additional positive attribute. This certain quality is likely due to the decomposition of cellulose, hemicellulose and lignin by microorganisms that leads to humic substances, like fulvic and humic acids, which serve as buffers in soil (Nkoa, 2014). By adding digestate as a soil amendment, research has consistently shown that it can improve the quality of soil in terms of its microbial biomass, and nitrogen, and phosphorus content (Nkoa, 2014).

In addition to amending the soil, by creating this analogue, an operator can use AD to displace the largest consumption of on-farm fossil fuel: synthetic fertilizer, consisting of 29% of the energy consumed by agriculture (Miranowski, 2004; Hitaj and Suttles, 2016). As the transition from fossil fuels is duly important, AD's nutrient management ability directly serves this societal goal, and is additionally the single most mentioned motivator by the operators interviewed. For this reason, it can be argued that AD needs to correct another misconception. Instead of considering AD as a renewable energy technology, it may be better reconceptualized as a nutrient management technology primarily that has the ability to produce renewable energy secondarily. The misconceptualization may help operators that struggle precisely with its nutrient management, who may be under a false conception that this technology's main purpose is to produce energy. One operator described this scenario:

> "One of the things we've also discovered while researching the digester is that very few companies pay attention to the back end...If you don't account for that you're hamstruck. You're going to struggle with that, and basically constrict your element of growth." (I7)

So by reframing AD to focus on its major benefit, nutrient management, instead of overemphasizing its renewable energy capabilities, the challenge mentioned in 15/20 interviews of "how to deal with the waste water stream after the digester" (I1) may be rightly prioritized, and the impact it makes on the world will be strengthened.

On the foundation of its reconceptualization as a nutrient management technology, it is important to acknowledge and appreciate a foremost idea identified by this research that there are three major management categories. These categories have their subsequent challenges, but overall, when executed properly, are also the major economic streams and/or cost displacements and, furthermore, offer areas of growth for the industry. Simply, the management categories are 1) feedstock acquisition and feeding management (nutrient management inflow), 2) biogas and energy production management (secondary valuable byproduct), and 3) effluent management (nutrient management outflow). During the adoption period, each of these management categories needs to be considered ahead of time to thereby prevent complications and restrictions to growth.

Lastly, it is important to note that the results of this research tend to emphasize AD in a wet environment. Many of the management techniques may be the same in dry environments, where dry lots are used, but as those operators did not participate in this survey, it is likely that the management categories are subsequently biased towards moister climates, which can pose its own benefits and challenges.

2.5.1 Feedstock management

To make an AD system run properly, it needs to be fed. As one put it, "you cannot not have any food for it" (I9). The management of feedstocks can be broken into two categories: feedstock acquisition, and feeding management.

To amply feed, many operators seek and secure offsite feedstocks. This becomes a major preoccupation and challenge (as mentioned in 13/20 interviews), as good feedstock streams can be fickle and those that are received affect the health of the digester itself, as well as the quality and quantity of material that needs to be managed post-digester. Here, recognizing its importance, 18/20 of the interviewed operators shared their developed knowledge on feedstocks (the materials that enter the digester) and their feeding strategies.

When adopting a digester, it is important to consider if one will accept feedstocks and if one does, where will these feedstocks come from. As mentioned by the operators, there is a variety of feedstocks that can be fed to the digester and in general the feedstock market is bountiful. As shown by this research, it is highly recommended that during the adoption period, an operator should identify the environment of potential feedstock suppliers and transporters (mentioned in 15/20 interviews) in their area. These markets, as described by Ward et al. (2008), are variable and their differences are based in lifestyle and cultural differences, particularly in regards to recycling and food waste production. An understanding of how these feedstocks are going to get to the digester is imperative as well, acknowledging that proximity (14/20) of these resources affects their availability. To further exemplify this point, one operator mentioned they were close to the border and “there’s not a lot of big manufacturers around” (I18). If an operator can accurately assess the feedstock market around them, and their competition for these resources, they hopefully will be able to use organic solid wastes to, as this research shows, boost gas production, provide an additional stream of income, improve the ‘pumpability’ of the digestate onto the fields, divert organic material from landfills, and can have a positive effect on the brand of the business within the community, and also their crop productivity.

Another issue, beyond the geographic access to feedstocks, is securing a constant and continuous flow of the quality and quantity of nutrients needed for AD. For both simplicity and for the health of the microbial population within the digester, consistency of feedstocks is key. Unfortunately, the feedstock flows can be fluctuant. Securing multiple feedstock contracts with different suppliers may provide security in times of lost supply. Feedstock contracts guarantee a long term agreement on price, quality and quantity, and responsibility for standards met, to allow for the soundness of the AD biological and economic plan (Bouckley, 2019). For this reason, from this research, it has been found that some operators have relied on third party brokers to moderate the feedstock exchanges.

When securing a feedstock, it is important to consider quality, as mentioned in 13/20 interviews. Quality feedstocks, in terms of their biogas potential can be described by the research Gunaseelan (2004), Cho et al. (1995) and Moller et al. (2004). The quality (and quantity) of feedstocks can affect among others: 1) the tipping feeds received, 2) the health of the digester, 3) the biogas production potential, 4) the volume of effluent filling the storage lagoon, and 5) the capacity of the crop fields to accept the nutrients spread. So considering these factors, an operator must balance the flow of feedstocks coming in with the financial, biological, productive and space availability that accord with the goals of the operation. Sharing the responsibility, one digester operator mentioned relying on a microbiologist to help optimize the biological and biogas productive capacity of the feedstocks with the financial and supply chain management.

Tipping fees are, in general, a positive motivator for accepting feedstocks. Like a landfill, AD operators are paid by feedstock (organic waste) producers to handle and dispose of the material. They offer an additional stream of income and vary based on the feedstocks produced in the area. As one operator put it, “the only way to make a digester profitable is the tipping fees, we’ve found” (I15).   This research found that operators can augment tipping fees when the feedstock is less desirable to the AD process. This can be because they are inconsistent in quality, quality, or timing; hard to handle (e.g. contained in inorganic plastics); and/or the feedstock has qualities that increase the risk of biological upset. They also are influenced by the average going rate of tippings fees within the region. The Environmental Research and Education Foundation publishes yearly reports on the average tipping fees by state, which could be helpful when determining the normalized prices in a region and where AD might be best suited (EREF, 2021). If one ‘chases’ high tipping fees, one may receive more money from the tipping fees, but, as this research learned, may pose risks to the biological sustainability of the microbiota. If the biology of the AD isn’t optimal (i.e. the ‘bugs’ are not healthy), there will be no biogas productivity. Accepting differentially priced tipping fees, therefore, allows operators to control the feedstock flow.

There is one growing alternative way to augment the income stream from the feedstocks that varies state by state: carbon credits. These credits attribute value to the feedstocks by how much organic matter they divert, in terms of their subsequent methane emissions reduced, from landfills, which should roughly equate to how much emissions are captured by the AD (Binkley et al., 2013). They are recognized on voluntary markets like the Chicago Climate Exchange, where large power and manufacturing companies can voluntarily buy credits to reach sustainability goals (Bilek, 2006). The challenge with these being that it variably applies to animal manure or feedstocks, and applicability can vary state by state. It is suggested here that operators ascertain the availability of this opportunity when adopting their AD system.

In addition to quality, a significant restriction to growth and matter of concern is volume management, particularly the volume of storage and space for distributing the effluent post-digester as it relates to the feedstocks coming to the AD system. Unless an operator is nowhere near reaching the capacity of their manure lagoon or fields for nutrients, as this research found, one must account for the progressive lessening of storage capacity and field availability for the effluent. Subsequently, rationing the volume of feedstocks taken onsites becomes a priority of operators (mentioned in 7/20 interviews). Additionally, the engine generator that combusts the biogas for electricity has its own capacity limits to combusting the biogas. So pacing the feedstock to match the biogas combustion capacity may challenge the pre-digester feedstock storage capacity and/or the biogas storage capacity. Feedstock acquisition and usage is thus a balancing act of supply, storage, and distribution.

While the feedstocks greatly determine the quality of digester performance, how those materials are handled pre-digester and controlled within can affect the outcome as well. While not a major priority of this research, there were a few aspects of feeding management worth noting. Mixing the feedstocks together pre-digester is important. Mixing allows for greater access of organic matter with the microbial populations, as well as releasing gas bubbles from the material and preventing sedimentation, or in the words of the operators ‘sludge buildup’ (Ward et al., 2008). Interestingly, researchers have found that digesters performed better with mixing at low speeds than high ones, as excessive mixing can disturb microbial populations

(Stroot et al., 2001). Mixing is an imperative especially with codigestion, which has been shown to improve methane production (Alatrite-Mondragon et al., 2006). As some of the operators mentioned, pre-treating the materials coming in the digester can help with performance down the line. Research has shown that various pretreatment methods can positively affect the methanation of digesters. Gunaseelan (1994) found that pretreatment with alkali was able to increase methane production and breakdown cellulose at a greater rate than without the alkali pretreatment. Kim et al. (2003) found that using heat and chemicals ('thermochemical') to reduce particle size were able to increase methane production by 34% and decrease COD by more than 67% in waste sludge from a sewage plant in Korea. Angelidaki and Ahring (2000) found that reducing the particle size of the materials entering the digester by maceration significantly increased fiber degradation and biogas production. To concur with what one of the operators interviewed did, a pretreatment of inoculum, or 'seeding' has been shown to increase the digestion of fibers, reduce startup time, and reduce BOD (Ward et al., 2008). The world of pretreatments may be a significant area of growth for the US dairy industry.

A next aspect of feeding management is keeping the material within the tank warm. As this research found, inclement cold weather can pose significant risks to the activity of the digester. The microbes, specifically those producing methane, and enzymes are specifically affected and temperature can be a key limiting factor to an AD tank that is unsatisfactorily insulated (Yao et al., 2020). There is a growing field of research attempting to expand the ability of AD systems to overcome inapt climate, which has been found to be regions with average annual air temperatures of less than 8 degrees Celsius, including much of the northern hemisphere (Van Stempvoort and Biggar, 2008). The operators interviewed in this research, who were in climates ill suited, they used a variety of techniques to maintain temperature, including burying the tank underground to take advantage of natural geothermal heat and the earth's natural insulation and using the heat generated from the biogas cogeneration engine to heat the tanks. In accordance with the literature, insulation and using exhaust heat from the engine appear to be the most common ways of maintaining temperature (Yao et al., 2020). Insulation involves purchasing affordable and available construction materials with low heat transfer, which is the most common method in rural areas (Yao et al. 2020). Heating the system, as some of our interviewees did, poses an additional consumptive demand as it consumes the energy produced, thereby limiting the productive potential for energy used elsewhere (Fjortoft et al., 2014).

The realm of scientific progress related to adapting to cold environment extends beyond just insulation and self-generated heat. Researchers experimenting with digestion at extreme temperatures found that cold tolerant ('psychrophilic') bacteria were essential for AD of animal wastes at low temperatures, especially during the winter months of the northern American states (Nozhevnikova et al., 1999). Psychrophilic microbial inoculation proves to be a way of increasing efficiency during the cold weather months (Akila and Chandra, 2009). Additionally, researchers like Masse et al. (1996) have found that biogas production in cold weather digesters holding swine manure was increased with greater mixing of the feedstock pre-digester, allowing greater homogeneity and greater contact between the organic matter and microbial populations. If cold weather climates are predicted and investments are made upfront, researchers in Switzerland have developed a digester called an Accumulation-Continuous-Flow system, which, under low temperature (12-25C) conditions had comparable gas yields to mesophillic digesters, yet had 30-40% higher energy yield due to its low energy requirements (Sutter and Wellinger, 1988). The biological limits of cold temperatures can create issues for an AD operation, but solutions exist towards biological maintenance and productivity.

Lastly, knowing the signs of problems within the digester is incredibly important. As the operators interviewed mentioned, checking levels of CO2 and the consistency and quality of the bubbles leaving the digester are important parameters. Thanks to sensors and automation, much of the operating parameters that are necessary to monitor for optimum performance are relegated to computerization. However, Ward et al. (2008) outlines the parameters and asserts that these parameters are assessed in two phases: liquid and gaseous. Those parameters in the liquid phase are: volatile fatty acid content, pH, alkalinity (or buffering capacity), COD, and dissolved hydrogen (Ward et al., 2008). The parameters in the gaseous phase are: total gas production rate, gas composition, and also quantities of methane, carbon dioxide, hydrogen sulfide, and hydrogen individually (Ward et al., 2008). Ward et al. (2008) argues that because these parameters are not highly attended to, and the inherent instability that comes with fluctuant feedstocks, most digesters perform in a way to reduce risk instead of optimizing performance, way below their potential. Lohani and Havukainen (2018) describe ten rate limiting parameters that require attendance, those being: pH, temperature, C:N ratio, moisture content, particle size, organic loading rate, solids retention time, sulphate reduction, denitrification, and ammonia. For brevity's sake, we will discuss the first three. In the digester system, there are bacteria of different types and pH preferences. Lohani and Havukainen (2018) describe there being three major categories of bacteria: those involved with hydrolysis, fermentation or acidogenesis, and methanogenesis. A challenge to finding a balance in the digester is that the fermentative bacteria have optimal growth at a pH of 5.0-6.0 (Hwang et al., 2004), and the methanogenesis bacteria prefer a pH of 6.5-8.0, but can function at pH as low as 5.5 (Boe, 2006). A common source of error is the over accumulation of acids, and thus killing the methanogens and inhibiting the productive output (Lohani and Havukainen, 2018). In these situations, adding exogenous sources of alkalinizing agents like lime, carbonate, hydroxide, or bicarbonate can raise the pH into the preferred range of methanogenesis (Lohani and Havukainen, 2018). Without repeating the conversation previous, temperature is an important factor to digester productivity. Increasing temperature, in particular, has many advantages: increases hydrolysis of the feedstock, increases biological metabolism, decreases retention time, increases gas production, and increases the death rate of pathogenic bacteria (Lohani and Havukainen, 2018). Lastly, the C:N ratio of the feedstock slurry is a rough indicator of the essential nutrients needed for bacterial metabolism. Rajeshwari et al. (2000) report a C:N:P ratio of 100:3:1 for maximal methane yield.

As for the future, the growth of the industry in terms of feedstock acquisition could be improved in several ways. In states like CA, CT, MA, RI, VT, and the municipalities of Austin (TX), Boulder (CO), New York City (NY), San Francisco (CA), and Seattle (WA), there are laws that restrict organic matter from entering the landfill, also called Organic Waste Bans (Broad Leib et al., 2018) . These laws attempt to minimize food wastes and prompt organic waste producers to search out more sustainable options, including AD. Indubitably, these laws come with their political and logistical/infrastructure challenges, but if these laws could extend beyond their state lines, the potential for feedstocks available for AD would increase.

A technological advancement could be the adoption of depackagers, which can turn plastic contained organic matter feedstocks, which generally receive higher tipping fees, into more accessible products for the digester. By using depackagers, the breadth of feedstock available and the tipping fees available to the operator would increase. Popular brands include: DODA, Doppstadt, Dupps, Gemidan, Haarslav, Scott Equipment, and Ecoverse (Coker, 2019). Additionally, an expansion of the government mediated credit programs and tax incentives to promote organic waste diversion and greenhouse gas mitigation would surely promote AD implementation within agricultural, industrial and municipal waste streams. One operator mentioned creating a feedstock testing and approval process that shifted responsibility from the feedstock receiver to the feedstock supplier would simplify the process as there are usually many receivers and one supplier.

2.5.2 Biogas and energy production management

A main focus from the interviews was how biogas and its derived products including energy, heat, and fuel, provide a significant source of monetization, and the gatekeepers, utility companies, hold the key to this possibility. The power production potential for AD is tremendous (as mentioned in 13/20 interviews), attributable to the fact that digesters can produce energy 24/7/365 without fluctuations based on wind or daily variations in sun while also turning waste into a valuable nutrient resource. The challenge becomes how that power is valued by the utility company

From speaking to AD operators throughout the country, this research found that 14/20 explicitly mentioned working with the utility company when adopting and operating their AD system. That being said, 13/20 operators expressed issues/challenges with the utility. Utility companies are the arbiters of commercial value, and as the industry stands, particularly with the technology and power purchase agreements, utility companies hold control of the income stream.

The power purchase agreement (PPA) and the type of hookup create a particular economic relationship between the AD operator and the utility company that are worth noting. If one is in a buy-all-sell-all PPA then one's income stream and energy production potential is completely moderated by the utility company, as all electricity produced is sold and compensated at wholesale prices through the utility grid (Binkley et al., 2013). At the end of the day, however, the energy resource is exchanged for a monetary value that is fluctuant, based on the availability of other fuel sources and their demand. As prices fluctuate, securing the energy resource and having on-site use first to displace costs may prove a hedge against variable price risks.

If one has a net metering PPA, there is potential for offsetting one's costs before selling the surplus to the grid for credit, which can be applied to reduce the electric bill in a subsequent month (Binkley et al., 2013). Here, no matter the price of energy, the energy produced displaces current use, so the farm's use is prioritized first. The price of electricity from the utility could be 4 cents or $1.25 per kWh, but to the farm the energy is provided. Net metering allows for risk mitigation in the face of a changing energy landscape, in addition to an income stream of the surplus energy credited to the electric bill.

An interesting power purchase system is net metering plus island mode. As mentioned by some of the operators, grid failures can lead to AD failures:

> "Sometimes our utility will knock us offline if there are fluctuations in the utility. It'll knock us off line and shut things down, so it's not always a component failure but a utility failure that'll cause us problems...because we are tied to the grid all the time." (I16)

In traditional net metering PPA, while current use is "displaced," this is somewhat misconstrued. Energy produced is still sent to the grid, but its value is signified through a credit system whereby the energy produced is credited against the energy consumed from the grid. The grid power is still used, oftentimes to power the engine generator set, but the monetary value of it is displaced. As a result, when the grid "goes down" and delivery capabilities are hampered, consumption and sales are also inhibited. This leads us to an exemplification of why 'island modes' are important. Island mode permits energy usage onsite with or without grid ties, in conjunction with plus an income stream of the surplus energy, like net metering. Reasons for island mode configurations include a frequently interrupted and/or unreliable energy network (Clarke Energy, 2020). This involves extra capital injection to the project for a “radio controlled breaker” (I16), but can protect against utility failures. Notably, the operators who have the island mode attribute the success of their system to their utility being “extremely good to us” (I16). Here we can appreciate how a good relationship with a utility company can manifest into resilient electrical infrastructure for AD. Additionally, island mode allows for energy independence and dependability, which has its advantages in an energy landscape that is uncertain. Island mode seems to be an advantage for the future.

While many PPA’s and their subsequent income streams are mediated by utility companies, government agencies do create regulations that can intervene and create economically advantageous PPAs for AD operators that favor renewable energy production. These regulatory programs offer hope in the realm of biogas monetization. One repeatedly mentioned government intervention program is the Sustainably Priced Energy Enterprise Development (SPEED) program in VT. This program, developed in 2009, allows for a guaranteed rate for power production from renewable energy resources for long term contracts to minimize the effects of fluctuations or deflations of power pricing to cash flow of the renewable energy enterprise, as mediated by the Vermont Public Utility Commission (VEPP, 2021). Another program, also in VT, the Cow Power program, is a voluntary rate subscription program that allows commercial and municipal electricity consumers to choose whether or not to pay an additional 4 cents per kWh on their electric bill for green energy, which 100% is directed to farmers producing energy (Levine, 2013). While this is touted as a possible solution to the low rates paid for green energy, as this research found, skepticism remains as consumer consciousness and values towards farm based green energy depreciates over time and these types of voluntary rate programs may require positive public relations program to guarantee that electricity consumers want to continue paying for green energy.

An additional monetization strategy that adds to the price paid for renewable energy is renewable energy credits (RECs). RECs are payments made for every megawatt hour of total electricity produced and delivered to the grid, which is calculated by the utility company (Binkley et al., 2013). These credits are either owned by the power producer (i.e. the AD operators) or by the utility companies themselves, based on the terms of the PPA. These RECs are sold to the open market or brokered via third party brokerage firms, which allow companies to invest in green energy and meet their sustainability and/or greenhouse gas emission goals (Binkley et al., 2013). The challenge that this research found is that operators have grown wary of RECs as their value has depreciated over time, often in favor of gas credits that instigate biomethane production over electricity. This devaluation of REC poses a challenge to monetization of AD.

All of these aspects mentioned above, managing utilities, PPAs, installation infrastructure, government mediated incentivisation programs, highlight an important fact: utility companies are the gatekeepers of monetization and needed for the future of developing the industry. It behooves an operator during the adoption period to connect with their utility company, find out their policies about and financing strategies for renewable energy, and generate a power purchase agreement. Adding to the fact that the relationship and agreements made with the utility company may be some of the most valuable assets to the success of the AD, this research could easily offer reasons for public policy advocates to examine their role in influencing utility companies' stake and interest in PPA’s that promote AD power production. Proliferation of programs akin to the SPEED and Cow Power programs would be advantageous to the dissemination of AD technology.

Before the interface with the utility, biogas handling both poses challenges and opportunities for AD, as mentioned in 11/20 interviews. As previously described, the gas is combusted to generate energy, and oftentimes heat. That gas, though, often is processed precombustion to purify out contaminant gases, like hydrogen sulfide (H_2S), which can be foul smelling, corrosive to engine-generator sets, unhealthy to staff, and environmentally unfriendly (Abatzoglou and Boivin, 2009; Choudhury et al., 2019). Specifically, H_2S reacts with water vapor to produce through oxidation sulfuric acid, which causes corrosion (Choudhury et al., 2019). The process of purification, called scrubbing, is touted as being a way to decrease the hydrogen sulfide and thus increasing the longevity of the engine machinery, decreasing maintenance costs and increasing revenue with higher quality gas (Choudhury et al., 2019). As engines can be one of the most expensive components of a biogas production system, scrubbing can surely be a positive attribute (Allison Engineering, 2021). From the literature, there appears to be two major methods of scrubbing present on US dairy farms: biological desulfurization using sulfur-oxidizing bacteria (SOB) in a bio-trickling filter (BTF) scrubber, and physical-chemical absorption using iron oxide pellets or wood chips impregnated with iron oxide (Choudhury et al., 2019). The BTF scrubber, what the interviewed operators colloquially consider as a 'scrubber', injects oxygen into the environment of the SOB who use H_2S as their primary metabolic substrate (Choudhury et al., 2019). Schieder et al. (2003) found that BTF scrubbing systems, specifically BIO-Sulfex biofilters from Warsaw, Poland, were able to have a 90% reduction in H_2S levels. Iron oxide based 'iron sponges' oxidize with the H_2S, converting it to iron sulfide, ultimately reducing H_2S levels by >99.9% (Choudhury et al., 2019). The challenge to scrubbing, as found in this research and in the literature, in addition to financing, is management. Knowing when to replace and replacing the iron-oxide media after saturation, ascertaining whether biological conversion of H_2S is still happening, troubleshooting the BTF scrubber, these management operations require dedication to maintain H_2S scrubbing efficiency (Choudhury et al., 2019). But hiring full time operators to manage the scrubber efficiency can be uneconomic and prohibitive, especially for some AD farm based operators (Choudhury et al., 2019). This all being said, better scrubber management leads to improved scrubbing performance, but the long term costs of engine corrosion and repairs needs to be further researched to understand the relative advantage these instruments play to an AD operation (Choudhury et al., 2019).

From a different perspective, gas handling of AD provides a societal advantage to the farming operation: odor control (as mentioned in 14/20 interviews). These odors are public relations concerns for AD as they can affect the moods, psychological well-being and physiological responses of neighbors and passersby (Powers et al., 1999). Powers et al. (1999) found that a 20 day retention in AD lead to a 50% decrease in odor intensity, further reaffirming the conclusions made from this research. Lessening odor complaints serves a significant advantage “for political and public [relations] reasons” (I9), which is doubly confirmed through Penn State Extension (2012), particularly as more non-farm residents move to rural areas and the urban/rural interface becomes more pronounced.

As for the future of biogas, the anticipated technological advancement in gas transformation is the possibility for renewable natural gas (RNG). There are several advantages to this technological progression, as described by Angelidaki et al. (2018). Compared to other renewable energy production technologies like wind and solar, biogas technologies in general are highly dependable, as they do not fluctuate based on wind and solar availability (Angelidaki et al., 2018). As compared to raw biogas, which cannot be adequately stored for more than a few hours, biomethane (RNG) can be stored for months, allowing it to be used at peak demand (Angelidaki et al., 2018). As the complete electrification conversion of the national vehicle fleet is distant, RNG offers society as a renewable fuel source analogue that can be used to propel air, road, and sea transportation (Angelidaki et al., 2018). The growth of credit programs to incentivize the upgrading of biogas are also a burgeoning reason for technological progression. These programs include the Renewable Identification Numbers (RIN), which stem from the Renewable Fuel Standard developed in the Energy Policy Act (2005), California's Low Carbon Fuel Standard credits and Oregon's Clean Fuel Program credits (Pleima, 2019). The Renewable Fuel Standard sets standards for the required volume of renewable fuel sources that must be injected into the transportation sector's fuel supply (Pleima, 2019). RINs serve as the currency for accounting the volume of renewable fuel added, as each gallon of renewable fuel produced is able to generate a RIN (Pleima, 2019). These RINs are traded and sold by petroleum refiners and importers to meet compliance with the Renewable Fuel Standards (Pleima, 2019). RINs are further categorized by greenhouse gas (GHG) reduction potential; agricultural digesters, including dairy based digesters, fall with D3 RINs (60% GHG reduction, and more valuable), unless they also codigest food wastes then they create D5 RINs (50% GHG reduction) (Pleima, 2019). These RINs can be generated from injection into the natural gas grid (Pleima, 2019). The California's Low Carbon Fuel Standard credits and Oregon's Clean Fuel Program credits can be appended to the RIN program for improved monetization (Pleima, 2019). From this research, the industry is developing "hub and spoke" models for RNG. In this model, AD systems on multiple farms are configured in a relatively circular geographic arrangement. Each produces biogas and that biogas is sent to a compressor processing station centrally, which is injected into municipal

CNG pipes for RIN qualification. The challenge experienced by the oeprators interviewed is the financing of upgraded compression units from previously purchased engine generator sets and the accessibility of pipelines for injection. A question society at large should consider is: what should happen to the electricity producing AD operations that cannot afford nor are they situated appropriately for gas compression as the industry shifts towards biomethane? Society has a need for both renewable electricity and fuel, so creating economic viability in both forms of energy is imperative. This may mean protecting RECs from depreciation, while championing RINs.

2.5.3 Effluent management

Effluent management is described as being one of the “biggest challenges” (I1) and one of the biggest areas of growth for the industry. As a nutrient management technology, AD creates an effluent that can have many advantageous qualities if managed properly. This effluent can be separated into liquids and solids; the liquid portion can be used as a fertilizer analogue, as mentioned in 18/20 interviews, and the solids are dried and chiefly used as bedding for cows, as mentioned in 12/20 interviews, or for land application (Aguirre-Villegas et al., 2019). The impact of effluent management cannot be underestimated; it allows for the displacement of mineral fertilizers, subsequently lowering their environmental impact, increases the recycling of organic matter and nutrients, improves the cost savings to farmers by using farm-produced resources for bedding and fertilizers, as well as increases the nutrient efficiency of their crop fields (Al Seadi et al., 2012).

Separation, in addition to allowing the aforementioned advantages, improves a farms ability to store and transport the effluent, as mentioned in 8 of the 20 interviews. Separating the solids from the liquids improves the storage capacity of the liquids, which are stored in the previously-installed slurry ponds, while the solids are dried, stored, and transported elsewhere.

Separation itself, however, is a management challenge. Separation is often accomplished with screw presses, roller or filter presses and centrifuges (Guilayn et al., 2019). From this research, the operators mentioned finding a balance between separating too much and too little. As the machinery is energy consumptive, it costs money and time to separate the bedding. In addition to the costs, if one separates and dries the solids too much, as the solids are now dried and lighter than air, they become respiratory nuisances for the cows (I20). Likewise, as mechanical separation generally diverts nitrogen into the liquid fraction, and phosphorus into the solids fraction, more separation removes excess phosphorus from the liquid fraction to be used as a liquid fertilizer (Guilayn et al. 2019). On the opposite side, under-separation can create storage issues for the liquid and animal health issues, as the moisture contributes to the bacterial proliferation in the organic bedding material (Leach et al., 2015). Management of effluent separation indubitably requires attention and balance.

Another challenge seems to be the management of the beds. From this research, there was clear advantages ascribed to the bedding made from digested effluent: specifically, the bedding costs saved, the minimized bacterial growth, and the lack of moisture retention (I18, I3). However, there was also a counter argument presented. While the advantages of digested dried effluent are numerous, management styles may be different with greater attention and labor focused towards attending to the bed, especially when compared to sand bedding. Further research is necessary to determine if the benefits of solid fraction bedding outweigh the costs and diverted labor towards keeping the beds healthy for the animals, as compared to undigested dried bedding and sand. The alternative of sand is relatively incompatible to AD as it is abrasive to the AD machinery and pumps.

A note worthy of consideration and a definite area of growth for the field is specifically nutrient management. As bedding is often the primary use of the solids portion, the liquid portion is a nutrient rich material that lies in fertilizer value between livestock manures (undigested) and mineral fertilizers, depending on the feedstocks digested, and often equaling mineral fertilizers (Nkoa, 2014). This liquid portion is dispersed on fields for crop production using, most efficiently, injection and trail-shoe methods, which minimize surface area exposed to air and ensure rapid incorporation into the soil (Nkoa, 2014; Al Seadi et al., 2012). This must occur at certain times of year when nutrient uptake will be the most and runoff will be the least. According to AWSM Farming, a contract farming corporation in England, dispersion should best occur between the late winter through the end of summer, preempting crop growth, while avoiding times when the land is waterlogged, covered with snow or frozen, or when rain is forecasted within 48 hours (AWSM, 2019). Dispersion lessens effluent storage, and promotes the nutrient cycling and production of the crops needed for feeds. The challenge is that transportation is a limiting factor (Yao et al., 2020), times for dispersion are limited and overloading a field long term can be unsustainable (Larney and Hao, 2007). Overloading a field can degrade soil quality and be a source of nonpoint source pollution (Yao et al., 2020). AD systems are essentially nutrient centralizers that bring outside nutrients to one central location for creating greater biogas potential, yet it establishes the responsibility of nutrient dispersion to the AD operator. Ideally, AD operations have enough storage and acreage to disperse the nutrients that come onto the farm. At this locus, two solutions have emerged from this research that have been implemented by AD operators in the US. The first, simpler, is to integrate neighboring farmers into one's nutrient management plan. By including one's neighbors' fields, one may be able to accommodate the surplus nutrients and volume of the effluent. This may also curtail additional truck transportation costs and the use and wear of roads, increase the nutrient value of the neighbors' fields, diminish their fertilizer costs, and imaginably improve neighborly relations. Integrating neighbors into one's nutrient management plan may be a simple solution to reduce overloading on one's own fields and abate storage issues.

Another possibility, debated yet yearned for, is transforming the separated digestate into a material that is marketable and shippable. By doing this, nutrient overloading of local fields would be minimized, and nutrients would be allowed to reach fields beyond the immediate center of dispersion. One solution presented by an interviewed operator (I7) is registering the dried digestate as a bagged commercial fertilizer/compost. The counterargument asserted by several other operators is that the bagged compost market is highly competitive and saturated. One creative solution spurred by the industry is the creation of CowPots, created by the Freund Family Farm in New Canaan, CT (CowPots.com). What they have shown is that one can alternatively use the digestate to create a replacement for single use plastics, namely plant pots. The Freund family presses the separated solid digestate into a planter pot mold, then oven dries them, to be sold in their garden store and garden stores around the country as a biodegradable and sustainable gardening product. These planter pots allow moisture and root penetration and decompose post-planting in the soil (Jensen et al., 2016). The possibilities for replacing single use plastics do not need to end there. The molding process can make any shape. This process allows for the nutrients of the digestate to make their way beyond the farm in a way that is marketable, transportable, and displaces another use for petroleum: plastics.

As the industry matures, there is growing interest in advances in nutrient management, especially in liquid volume and nutrient dispersion management. From this research, the technological and policy advances that operators anticipate include liquid/solid separation technology able to remove a significant amount of nutrient and purify the wastewater enough to be dischargeable into a stream, effectively reducing the volume needed to be stored significantly and adding to the water table and/or irrigation water for those downstream. The challenge to this seemed not to be technical, but political. Membrane based technologies for water separation and purification for discharge have been actualized (Rongwong et al, 2018). EPA regulations from the Clean Water Act affecting point source pollution from livestock facilities, however, disallow discharging of effluent into a stream currently, no matter the form, purified or otherwise (Gollehon et al., 2001). This emphasizes that the regulatory future, in addition to the technological future, affects the success of AD.

2.6 Conclusion

In 2021, the British Petroleum Statistical Review of World Energy outlined the historic year that 2020 was in terms of its energy usage. Like no other year since 1945, due to the COVID-19 pandemic, 2020 had the largest decrease in global primary energy consumption and carbon emissions (British Petroleum, 2021). This fact, however, should not take away from the reality of oil depletion. According to BP (2021), there were 68.8 billion barrels of oil in US proven reserves and 1732.4 billion barrels in world proven reserves at the end of 2020. Extrapolating the 2019 high and the 2020 low values for yearly oil consumption to estimate longevity of these reserves, the world has between 48.6-53.6 years and the US has between 9.7-11.0 years (British Petroleum, 2021). As economic activity returns back to some semblance of pre-pandemic normal, one can hope that the consumptive patterns of fossil fuels will remain the same or lessen. Either way, the imperative for post-fossil fuel solutions becomes even greater in essentialness. Anaerobic digestion is one of those solutions.

As a renewable energy and a nutrient management technology, anaerobic digestion is management intensive. To this fact, and underpinning the main goal and hypothesis of this research, AD is a system of interrelated parts and management categories that require attention for productivity, economic stability, and environmental positivity to occur. The clearest and broadest conceptualization of the management categories, as found through this research, are 1) feedstock acquisition and feeding management, 2) biogas and energy production management, and 3) effluent management. Understanding and mastering how these management practices control the biological, mechanical, economic, and political aspects of AD will serve to grow one's individual enterprise and the industry itself. This requires learning from one's own system, from other operators in the industry, and from the body of academic work that spans the globe. It must be acknowledged that each operator must find particular solutions to their management challenges, as each AD system fits within an environment of feedstocks, policies, neighbors, climate, effluent sinks, among others, that are unique.

As Engler et al. (1999) suggests, manure management is a major factor in the future of sustainable livestock production, and AD is the technological system to champion that cause. AD can provide significant advantages to a farming operation, including generating revenue through tipping fees, and energy generation and crediting systems; displace costs for heat, electricity, bedding, mineral fertilizers; and improving one's nutrient recycling, crop productivity, and neighborly relations. These advantages come with attending to the management categories, and their subsequent sub-categories, for full performance.

As for the future, technology, policy and principally resource availability will enlighten the path forward. Technology to improve monitoring digestion parameters, automation, hydrogen sulfide scrubbing, biogas upgrading, and digestate valorization; policy to augment the incentives for feedstock acquisition, methane sequestration, biogas production and its subsequent energies, and waste management possibilities; and finally, the fossil resources that strategically compete with renewable resources. In a post-fossil fuel world, AD will play a significant part, especially for farmers, as they are mediators of huge amounts of 'waste' organic matter, ripe for energy utilization. The future of AD is bright, and for our nation, AD can provide plentiful sustainable and renewable energies. Honorably, the beginning of transition is the most difficult, and those interviews are pioneers of a burgeoning industry. These champions carry the industry onwards, and to them, this research is dedicated.

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APPENDIX A: SURVEY

ANIMAL SCIENCES
COLORADO STATE UNIVERSITY

Consent Question

Dear Participant,

My name is Alex Schaff, a master's student from Colorado State University in the department of Animal Sciences. The Principal Investigator, Dr. Noa Román-Muñiz, and I are conducting this research on anaerobic digestion waste management practices titled "Waste-to-Energy Enterprise Management".

We are requesting your participation in taking this anonymous online survey. Your voluntary participation will take ***approximately 10-20 minutes****. If you decide to participate, you may withdraw your consent and stop participation at any time without penalty.*

We will not collect your name or any personal identifiers unless you volunteer for an over-the-phone discussion for further elaboration of your responses. When we report our results, we will combine the data from all participants. Providing information from your experiences will benefit While there may be no direct benefits to you, we hope to gain more knowledge from your experiences on best practices of dairy waste management using anaerobic digestion.

While there are no known risks to participating in this survey, it is not possible to identify all potential risks, but we have taken reasonable safeguards to minimize any known and potential (but unknown) risks.

If you have any questions about the research, please contact Dr. Román-Muñiz at noa.roman-muniz@colostate.edu or Alex Schaff at alexander.schaff@colostate.edu. If you have any questions about your rights as a volunteer in this research, contact the CSU Institutional Review Board at RICRO_IRB@mail.colostate.edu; 970-491-1553.

Sincerely,
Alex Schaff
Graduate Student in Animal Sciences at CSU

Noa Román-Muñiz, MS, DVM
Associate Professor
Extension Dairy Specialist

STATEMENT OF CONSENT:
By clicking "Yes, I consent to participate" below, I am confirming my consent to participate in this survey. I understand the above information, and I freely choose to participate.

- ○ Yes, I consent to participate.
- ○ No, I do not consent to participate.

Screening

What best describes your role in anaerobic digestion?

- ○ a) Grade A dairy producer involved in anaerobic digestion
- ○ b) Anaerobic digestion operator
- ○ c) Dairy producer with no involvement in anaerobic digestion
- ○ d) Not a dairy producer and no involvement in anaerobic digestion.

Survey 1

How many total lactating and non-lactating dairy animals (including replacement heifers) contribute to the wastes you manage with your anaerobic digester?

Lactating dairy animals:	[▾]
Non-lactating dairy animals:	[▾]

What type of housing do you provide?

- ○ a) Tie-stall barns
- ○ b) Open/dry-lot
- ○ c) Compost barns

- d) Free-stall barns
- e) Cross ventilated barns
- [ ] f) Other or combination, please describe:

What type of anaerobic digester do you operate?

- Complete mix
- Plug flow (horizontal)
- Plug flow (vertical)
- Plug flow (modular)
- Plug flow (mixed)
- Covered lagoon
- Fixed film
- [ ] Other:
- Unsure

How many employees or full-time equivalents operate your anaerobic digester?

For how many years has your operation utilized anaerobic digestion technology?

	Years											
	0	5	10	15	20	25	30	35	40	45	50	
Time utilized												

Please describe how wastes were managed before anaerobic digestion:

What were the most important motivations to adopt anaerobic digestion as your waste management practice?

The next two questions consider the challenges of adopting anaerobic digestion:

What were the greatest challenges faced during the adoption period? Please indicate what phase (described below*) each challenge occurred.

How were these challenges solved?

*Four phases of anaerobic digestion technology adoption:

- **Consultation phase:** Preliminary interest in anaerobic digestion inspires decision makers to consult experts to understand feasibility.
- **Design phase:** Designs are made with project developers, engineers, and contractors. Outside governmental or other financial assistance investigated; town/county ordinances followed. This phase ends at the groundbreaking.
- **Construction phase:** Building of the anaerobic digester begins. This phase ends at the structural completion of the anaerobic digester.
- **Preliminary operation phase:** The first year of operation. During this time, microbial fauna stabilized, biogas concentrations and yields optimized including the coordination of inputs and outputs, fulfilling negotiations with feedstock suppliers, utility companies, and adapting personnel to operating the new technology.

The following questions consider the challenges of acquiring feedstocks for co-digestion. (Feedstocks are the organic inputs and main constituents of the anaerobic digestion process.)

Do you co-digest other organic materials in addition to the on-site wastes?

- Yes
- No

What materials do you co-digest?

	Yes	No
Agricultural residues	○	○
Food processing wastes (including dairy processing wastes)	○	○
Fats, oils, and greases	○	○
Commercial food wastes	○	○
Manures not from dairy animals	○	○
On-site facility processing water	○	○
Municipal waste water	○	○
Other:	○	○

Please describe what you are co-digesting:

[ ]

If accepting manures not from dairy cows, from what animals do you accept manures? At what quantity? If not accepting manures from a certain animal type, zero is an appropriate response.

Tons/month

0 10 20 30 40 50 60 70 80 90 100

Beef cattle: [ ]

Swine: [ ]

Poultry: [ ]

Other, please describe: [ ] [ ]

Please describe the greatest challenges in acquiring feedstocks and in maintaining both good quality and quantity of these feedstocks:

What solutions emerged from these challenges?

The following questions consider the challenges of biogas optimization and utilization:

What is your average methane concentration (% methane/total volume of biogas)?

	Percentage										
	0	10	20	30	40	50	60	70	80	90	100
Methane concentration											

How do you utilize the biogas? (check all that may apply)

- ☐ Flared continuously
- ☐ Electricity for on-farm/on-facility use
- ☐ Combined heat and power (CHP)
- ☐ Boiler/furnace fuel
- ☐ Electricity sold to electric grid
- ☐ Compressed natural gas
- ☐ Cooling water
- ☐ Other, please explain:

What is the annual electric yield of your operation (kWh per year)?

The three major power purchase agreements for selling electricity from anaerobic digestion (AD) to utilities:

- **Buy all - sell all:** AD operators sell all of the energy produced at a set rate to the local utility and purchase back the electricity needed to operate on-site.

- **Surplus sale**: Energy made and utilized on site, displacing energy grid consumption. Customarily, the energy needed, yet not produced on-site, is bought at retail price. Surplus energy - energy produced greater than total consumption - is sold to utilities at a marginal wholesale price.
- **Net metering:** Produced energy used onsite if electricity consumption is greater than production. If electricity production is more than consumption, the surplus electricity is sent to the grid and producers are accredited payments for next month's energy purchases. Essentially, it is credit system that operates through rollover discounts for future electricity consumption.

How would you best describe your power purchase agreement?

- Buy all - sell all
- Surplus sale
- Net metering
- Other, please describe:

Please describe the major challenges in negotiating the sale of energy with utility companies:

What solutions emerged from these challenges?

Do you accept renewable energy credits?

- ○ Yes
- ○ No

If not accepting renewable energy credits, please describe why not:

Please describe the most influencing factors in choosing the mode of energy utilization at your operation?

The following questions consider the challenges of digestate utilization. (Digestate is the nutrient-rich output of anaerobic digestion.)

How is the digestate used? (check all that may apply)

- ☐ Compost (aerobic decomposition)
- ☐ Thermophilic Pasteurization
- ☐ Bedding for animals
- ☐ On farm field application i.e. fertigation
- ☐ Biorefining to platform chemicals e.g. esters, alcohols, urethanes
- ☐ Digeponic soil additive (for greenhouses)
- ☐ Sold off-farm to agricultural/horticultural businesses

Where is the digestate composted?

- On-site
- Off-site

What were the greatest challenges in transporting and handling the digestate?

What solutions emerged from these challenges?

Do you separate the solid/fiber from the liquid/liquor portion

- Yes
- No

Do you market both portions?

- Yes
- No

Please describe the most influencing factors in choosing the mode of digestate utilization at your operation:

Please describe the major challenges faced in selling the digestate:

What solutions emerged from these challenges?

What type of anaerobic digestion system would best describe your operation?

- ○ Farm Scale
- ○ Centralized/Regional
- ○ Multiple farm/facility
- ○ Other, please describe:

Please describe the most influencing factors in choosing the system of your anaerobic digester:

Since adoption of the technology, please describe the level of difficulty (1 = least difficult, 5 = most difficult) for the following aspects of anaerobic digestion management:

	1	2	3	4	5

		1	2	3	4	5
Daily operation and maintenance of the anaerobic digestion machinery	O	O	O	O	O	O
Biology of anaerobic decomposition and biogas optimization	O	O	O	O	O	O
Training and managing personnel to operator the digester	O	O	O	O	O	O
Acquiring of feedstocks and negotiations with feedstock suppliers	O	O	O	O	O	O
Utilization and selling of biogas and negotiations with utility companies	O	O	O	O	O	O
Utilization and selling of digestate and negotiations with digestate buyers	O	O	O	O	O	O
Establishing and coordinating the cooperative practices of the enterprise	O	O	O	O	O	O
Financing and utilizing federal, state, or private/local funding	O	O	O	O	O	O
Permitting and complying with regulations	O	O	O	O	O	O
Ensuring biosecurity while handling digestate and biogas	O	O	O	O	O	O
Other, please describe:	O	O	O	O	O	O

What public policy recommendations would you offer to facilitate anaerobic digestion adoption among other dairy producers?

What challenges have you experienced that you wish the scientific community or industry could solve?

Regarding your current anaerobic digestion (AD) technology, please state your level of agreement to the following statements:

	Agree	Somewhat agree	Neither agree nor disagree	Somewhat disagree	Disagree
AD integrated well into the farm operation.	O	O	O	O	O
AD improved the energy independence of the operation.	O	O	O	O	O
AD improved the financial security of the operation.	O	O	O	O	O
AD improved the safety and hygiene of animal waste handling.	O	O	O	O	O
AD makes me a better neighbor.	O	O	O	O	O
AD has been a worthwhile investment.	O	O	O	O	O

What was the total upfront cost to build the anaerobic digestion technology?

What are the current annual operating costs for the anaerobic digester?

What is the current annual revenue for the anaerobic digester?

How many years has/will it take(n) to make a positive return on investment?

Further elaboration of your responses would be very helpful. Would you be open to an over-the-phone interview?