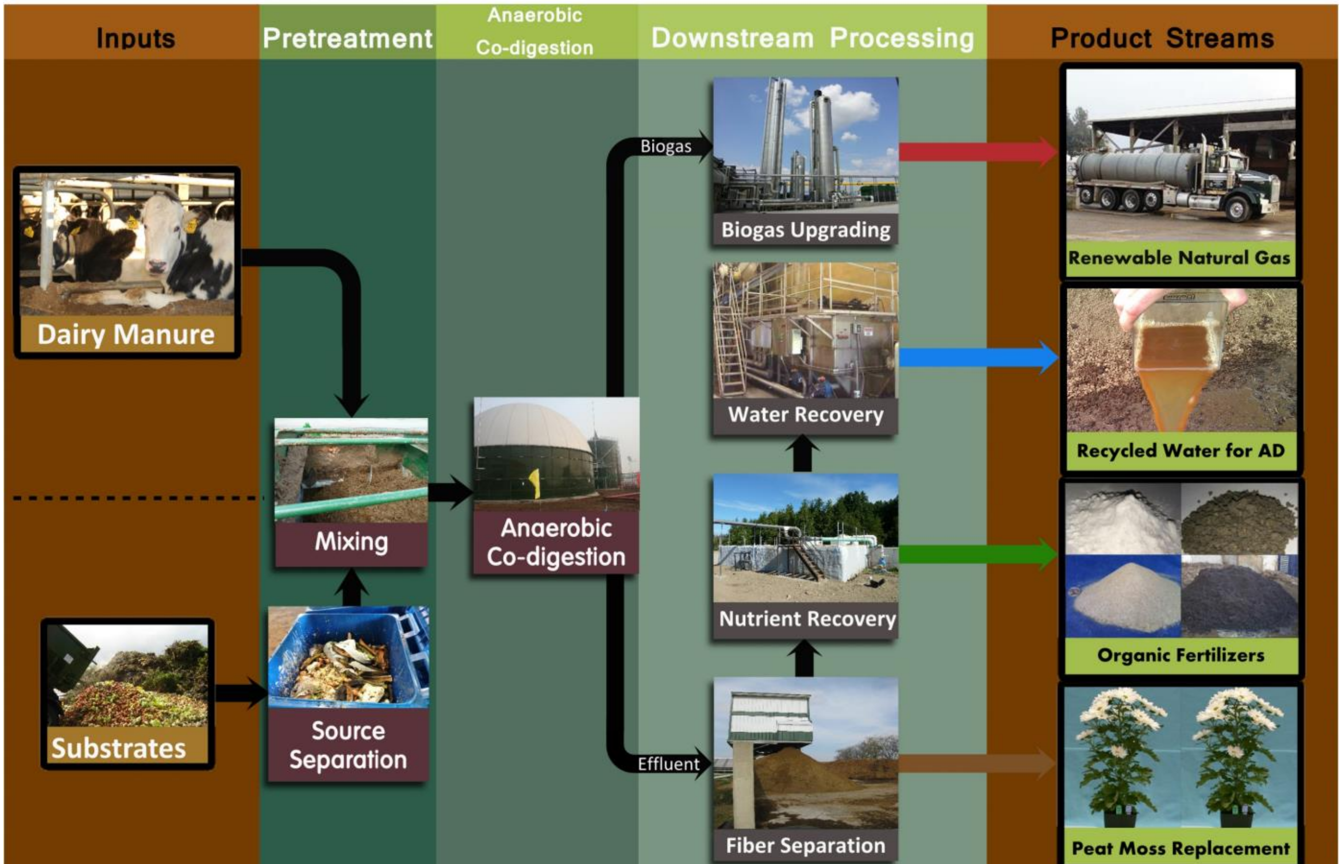

THE DAIRY BIO-REFINERY

The Anaerobic Digestion Systems Series provides research-based information to improve decision-making for incorporating, augmenting, and maintaining anaerobic digestion systems for manures and food by-products.

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THE DAIRY BIO-REFINERY

By,

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Abstract

Anaerobic digestion is a notable waste management technology that produces renewable energy while improving livestock manure management. The process reduces the release of greenhouse gas emissions (GHGs), volatile organic compounds, pathogens, and odors. Since their inception, some dairy digesters have used “add-on” technologies to improve project economics and address other environmental and management concerns. These add-on technologies convert traditional dairy digesters into dairy manure bio-refineries that integrate the core anaerobic digester with additional downstream equipment to generate value-added products including fuels, power, and chemicals. This publication provides an overview of the bio-refinery concept as applied to a dairy digester, and describes the technologies currently receiving the most interest for use with on-farm dairy digesters.

This publication serves as an introduction and overview for the Anaerobic Digestion Systems Series, which provides research-based information to improve decision-making for incorporating, augmenting, and maintaining anaerobic digestion systems for manure and food by-products.

List of Abbreviations:

AD	Anaerobic Digestion
CH_4	Methane
CHP	Combined Heat and Power
CNG	Compressed Natural Gas
CO_2	Carbon Dioxide
COD	Chemical Oxygen Demand
FC	Fecal Coliform
FOG	Fats, Oils, and Grease
GHG	Greenhouse Gas
H_2S	Hydrogen Sulfide
K	Potassium
LNG	Liquefied Natural Gas
N	Nitrogen
P	Phosphorus
PSA	Pressure Swing Adsorption
RIN	Renewable Identification Number
RNG	Renewable Natural Gas
TS	Total Solids
VFA	Volatile Fatty Acid
VS	Volatile Solids
WSU	Washington State University

Introduction

As of April 2018, there were approximately 205 operational manure-based dairy anaerobic digesters (ADs) in the United States (US), serving less than 6% of the US dairy herd (US EPA AgStar 2018). AD breaks down livestock manures and other organic material to produce biogas containing methane (CH_4), a source of renewable energy. It also simultaneously mitigates many air and water quality concerns by reducing the release of greenhouse gases (GHGs), volatile organic compounds, pathogens, and odors (US EPA 2008; Martin and Roos 2007; US EPA 2006).

Most existing dairy digesters in the US use the biogas to generate electricity and heat, also known as combined heat and power (CHP) (US EPA AgStar 2016). Ideally, revenue from the electricity pays for capital and operation costs for the AD project and adds to the dairy's revenues. In addition to biogas, AD projects often generate two other valuable products: fibrous solids that have multiple potential uses, and environmental credits resulting from the mitigation of GHGs.

Since their inception, some dairy digesters have experimented with "add-on" technologies to enhance the value of the products generated. This effort has intensified in recent years, as falling electrical rates received by US dairy farmers from power companies have made it difficult both for current AD projects to remain viable and new projects to be developed and constructed (Costa and Voell 2012; Coppedge et al. 2012). Increasing regulatory pressures relating to nutrient management have also contributed (Costa and Voell 2012; Yorgey et al. 2014). These complementary add-on technologies that generate higher value or additional products, and which may assist in nutrient management, convert traditional dairy digesters into *dairy manure bio-refineries* (Mountraki et al. 2016; Astill and Shumway 2016a; Bell et al. 2014; Jungmeier et al. 2014). In the case of the dairy digester, most of these additional technologies have been modified from the wastewater treatment and oil and gas industries to fit the economic and practical constraints of dairy operations. Many of the technologies are still in development, with additional research and commercialization needed to improve performance, enhance synergies between various technologies, increase efficiency, and reduce capital and operation costs (Drosg et al. 2015).

This publication, designed for farmers, third party project developers, regulatory agencies, and other stakeholders, introduces the *Anaerobic Digestion System Series*, and the bio-refinery pathways currently receiving high levels of interest for dairies. This publication does not describe particular technological approaches for AD system components, as these are described in-depth in other publications within the *Anaerobic Digestion System Series*. Publications within the series assume some familiarity with AD on dairies; readers who are unfamiliar with AD can refer to *Anaerobic Digestion Effluents and Processes: The Basics* (Mitchell et al. 2015).

To better highlight the bio-refinery concept, this factsheet compares a "traditional" manure-only AD facility with a bio-refinery that incorporates several additional treatment processes and technologies. Figure 1 provides an overview of the dairy manure bio-refinery concept, with three major steps: pretreatment of organic wastes, anaerobic co-digestion of organics, and downstream processing of products.

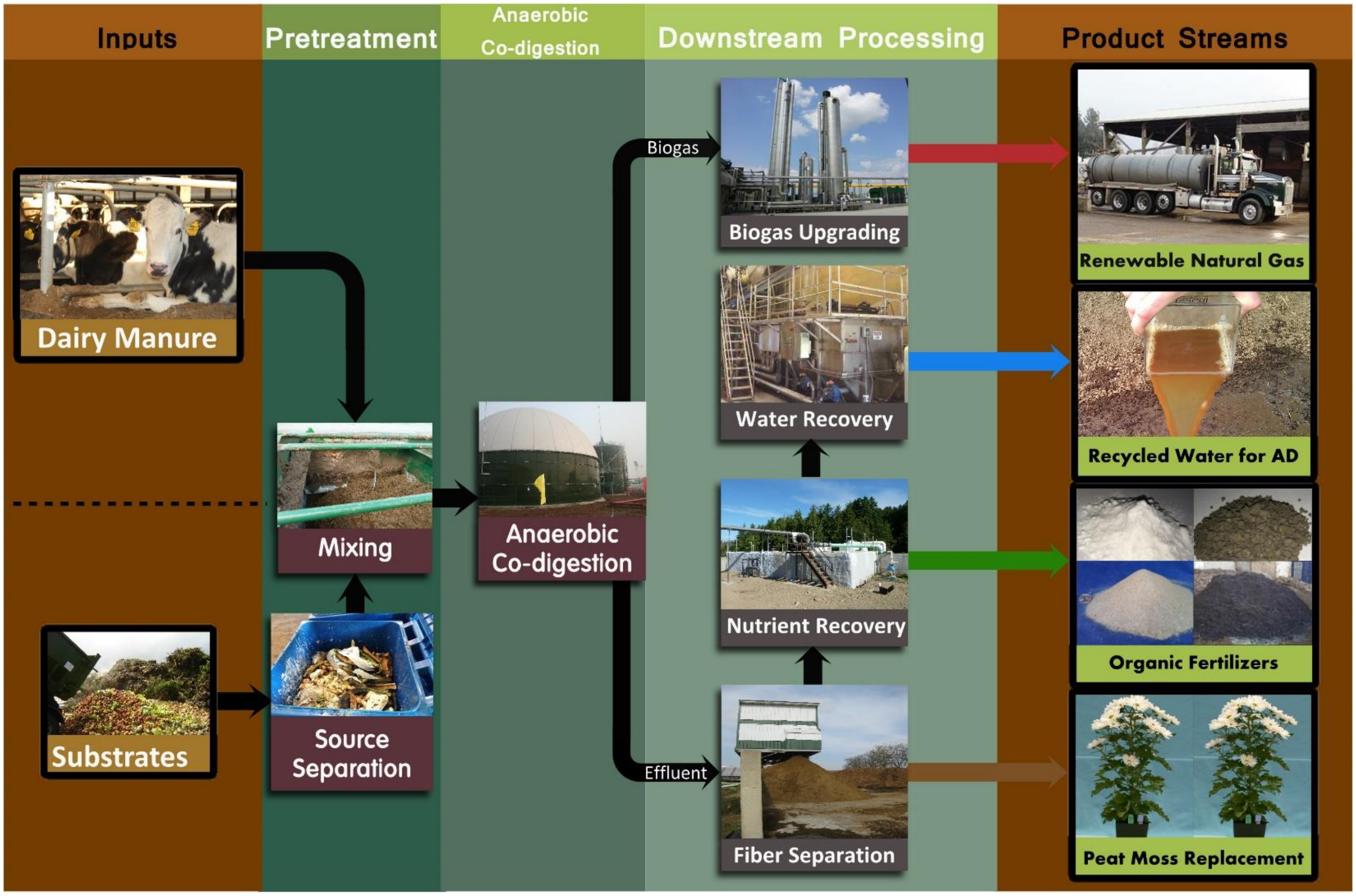

Figure 1. Dairy manure bio-refinery with associated processes and products. Graphic by Nicholas Kennedy and Jingwei Ma. Photos courtesy of American Biogas Council, Regenis, DVO Inc., Keith Bowers, Craig Frear, Jim Jensen, and Rita Hummel.

Pre-Treatment

In both traditional dairy digesters and dairy manure bio-refineries, dairy manure is the main feedstock processed in the AD vessel. However, to boost biogas production and improve economics, high energy off-farm organics can be added to the manure (Figure 2; Astill and Shumway 2016a; Attandi and Rahman 2012; Bishop and Shumway 2009). Some of the most commonly used high energy organics, referred to as substrates, include pre-consumer food processing wastes (e.g., egg breakage, whey), and fats, oils, and greases (also referred to as FOG). Fibrous substrates such as field residues or energy crops can also be added, and this is common in many parts of Europe, though not common in the US (Murray et al. 2014). In some areas of the US, many types of organic wastes may be available, and the digester owner or operator may receive a payment (commonly called a "tipping fee") for accepting the waste. In other areas, organic wastes may be limited or need to be purchased. For more information on co-digestion refer to *On-Farm Co-Digestion of Dairy Manure with High-Energy Organics* (Kennedy et al. 2015a), *Considerations for Building, Operating, and Maintaining Anaerobic Co-Digestion Facilities on Dairies* (Kennedy et al. 2016), and *Anaerobic Co-Digestion on Dairies in Washington State: The Solid Waste Handling Permit Exemption* (Yorgey et al. 2011).

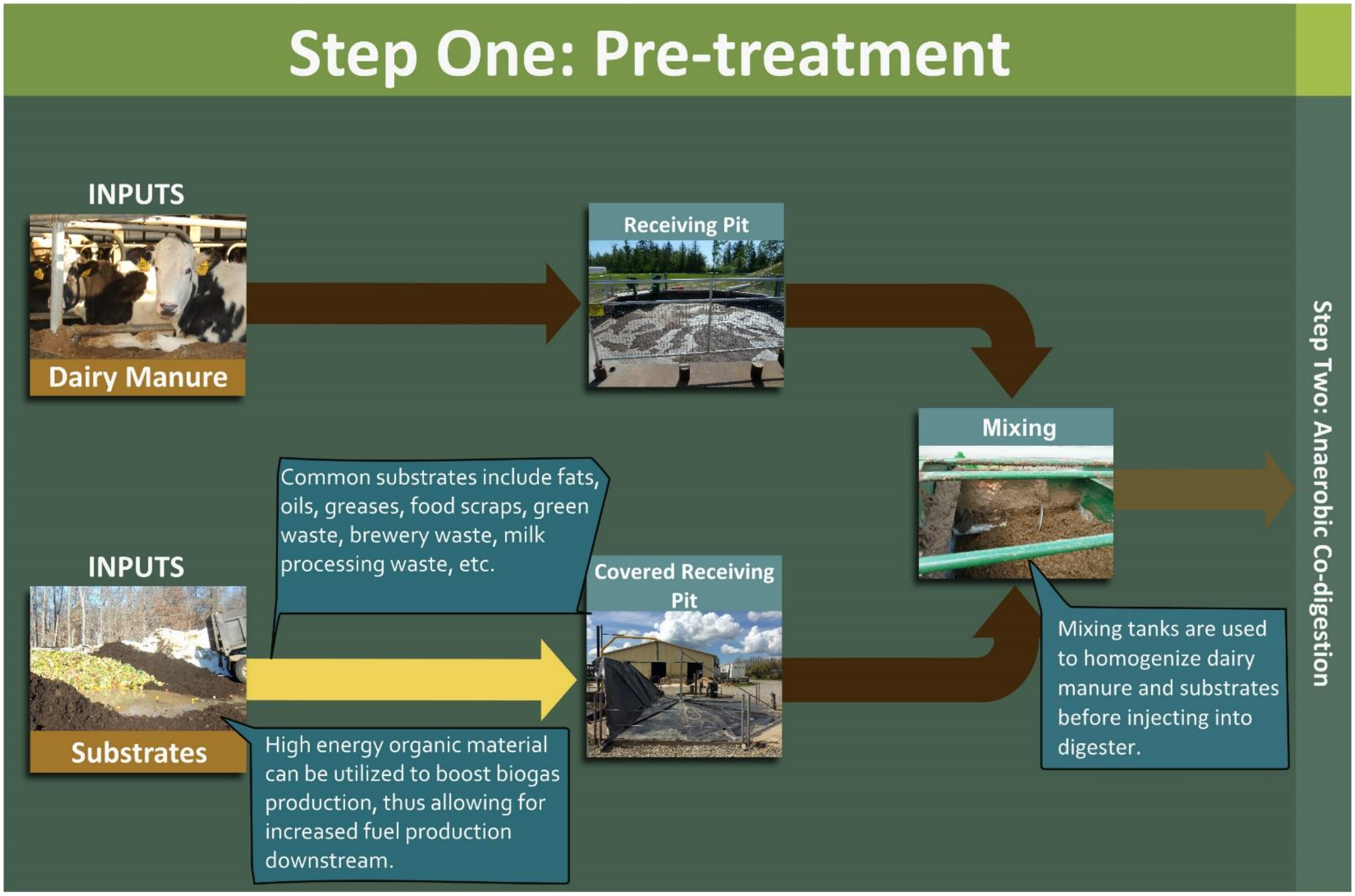

Figure 2. Pretreatment step for dairy manure and substrates. Graphic by Nicholas Kennedy. Photos courtesy of Regenis, Jim Jensen and WSU Energy, and DVO Inc.

Depending on the type of substrate being co-digested, pretreatment may be needed. For example, source separation may be required to remove unwanted inorganics, such as plastics and metals, with numerous de-packaging and separation systems now available for use on AD projects (Sullivan 2012). Meanwhile, co-digestion with recalcitrant organics such as field residues normally requires extensive pretreatment to break down lignocellulosic structures and make the feedstock more digestible. There are many biological, chemical, mechanical, and thermal processes for pretreatment—but beyond simple mechanical treatment, such as maceration for particle size reduction, most methods are too cost intensive to be viable currently on dairies in the US (Ariunbaatar et al. 2014; Carrère et al. 2010; Hartmann et al. 2000; Angelidaki and Ahring 2000; Biswas et al. 2012).

As shown in Figure 2, after pretreatment, substrates and animal manure are generally put in separate receiving pits and then mixed. Separation allows for control of mixing rates to maximize gas production and synergy between substrates and dairy manure. Ideally, receiving pit design also ensures effective management of odors and vectors during loading and storage of substrates, with features that may include tanks with biofilters or negative-air buildings as needed.

Anaerobic Co-Digestion

After mixing, substrates and dairy manure are sent to an AD vessel, the main waste conversion technology (Figure 3). AD is a complex process that utilizes various microorganisms to break down organic matter. During AD, different microorganisms split macromolecules, including fats, proteins, and carbohydrates into shorter molecules, such as fatty acids, amino acids, and sugars. These in turn are converted to even smaller molecules such as acetic

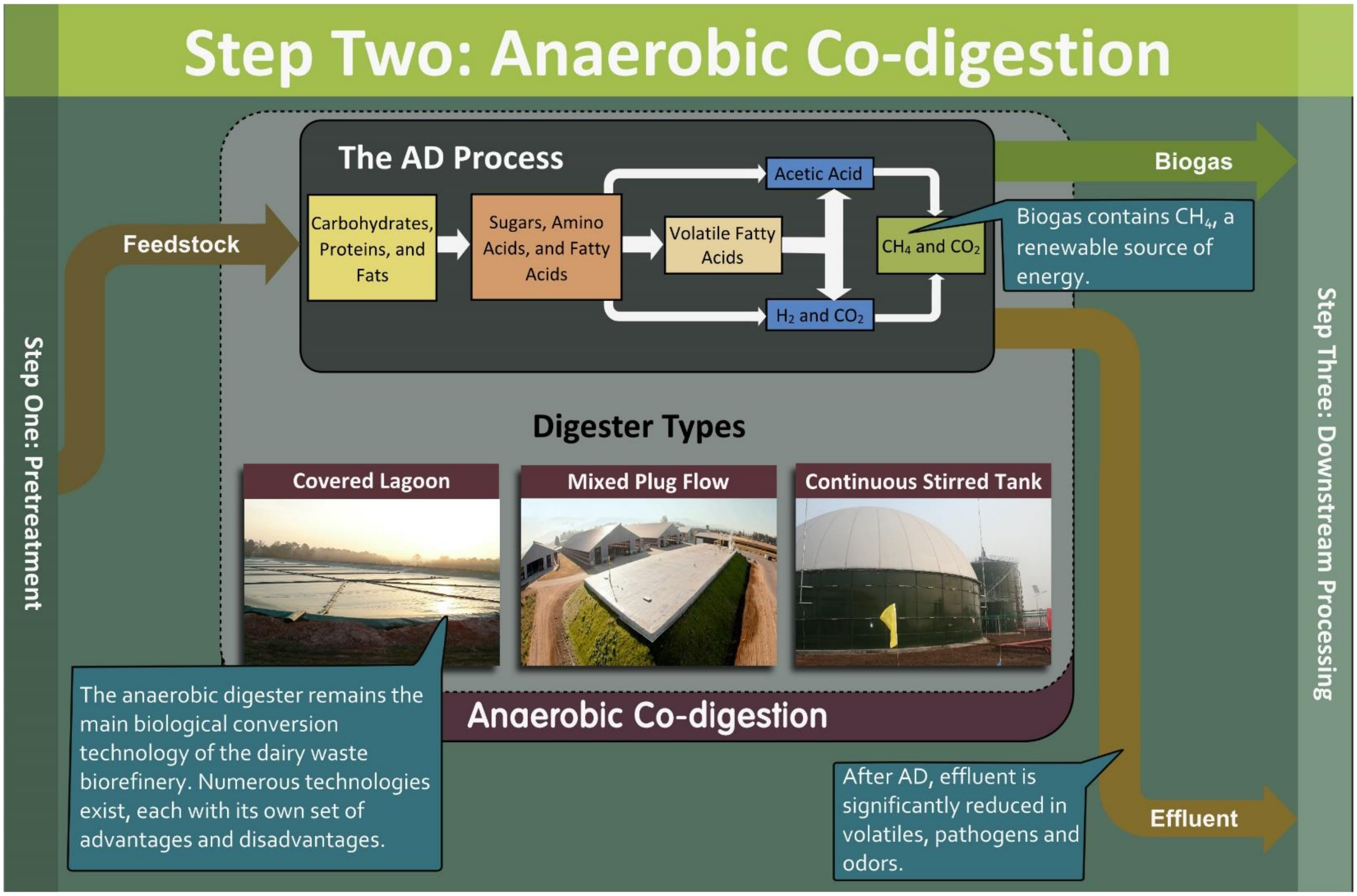

Figure 3. AD co-digestion with its associated products: biogas and effluent. AD process modified from Amaya et al. (2013) and Hamilton et al. (2012). Graphic by Nicholas Kennedy. Photos courtesy of American Biogas Council, DVO Inc., and Environmental Credit Corp.

acid. In the final step these small molecules are converted by another cohort of microorganisms into energy-rich biogas which can be collected from the headspace of the digester.

Meanwhile, many other advantageous transformations occur in the digester. Odorous compounds and pathogenic bacteria are greatly reduced. In addition, the organic material is in-part stabilized, with reduced chemical oxygen demand (COD), volatile solids (VS), and total solids (TS). For more information on anaerobic digestion, see *Anaerobic Digestion Effluents and Processes: The Basics* (Mitchell et al. 2015).

Downstream Processing and Products

After AD, both biogas and the remaining digester contents (effluent) are sent for downstream processing. In a traditional dairy digester, biogas is used to produce electricity and heat. This represents a relatively low value use of biogas. Another important product is fiber, which is most often separated from the effluent and used as animal bedding. Liquid effluent, along with the associated nutrients, is most often applied to field crops at agronomic rates. This field application step is like the land application that occurs in the absence of a digester—especially since digestion does not appreciably lower the amount of nutrients in the manure stream.

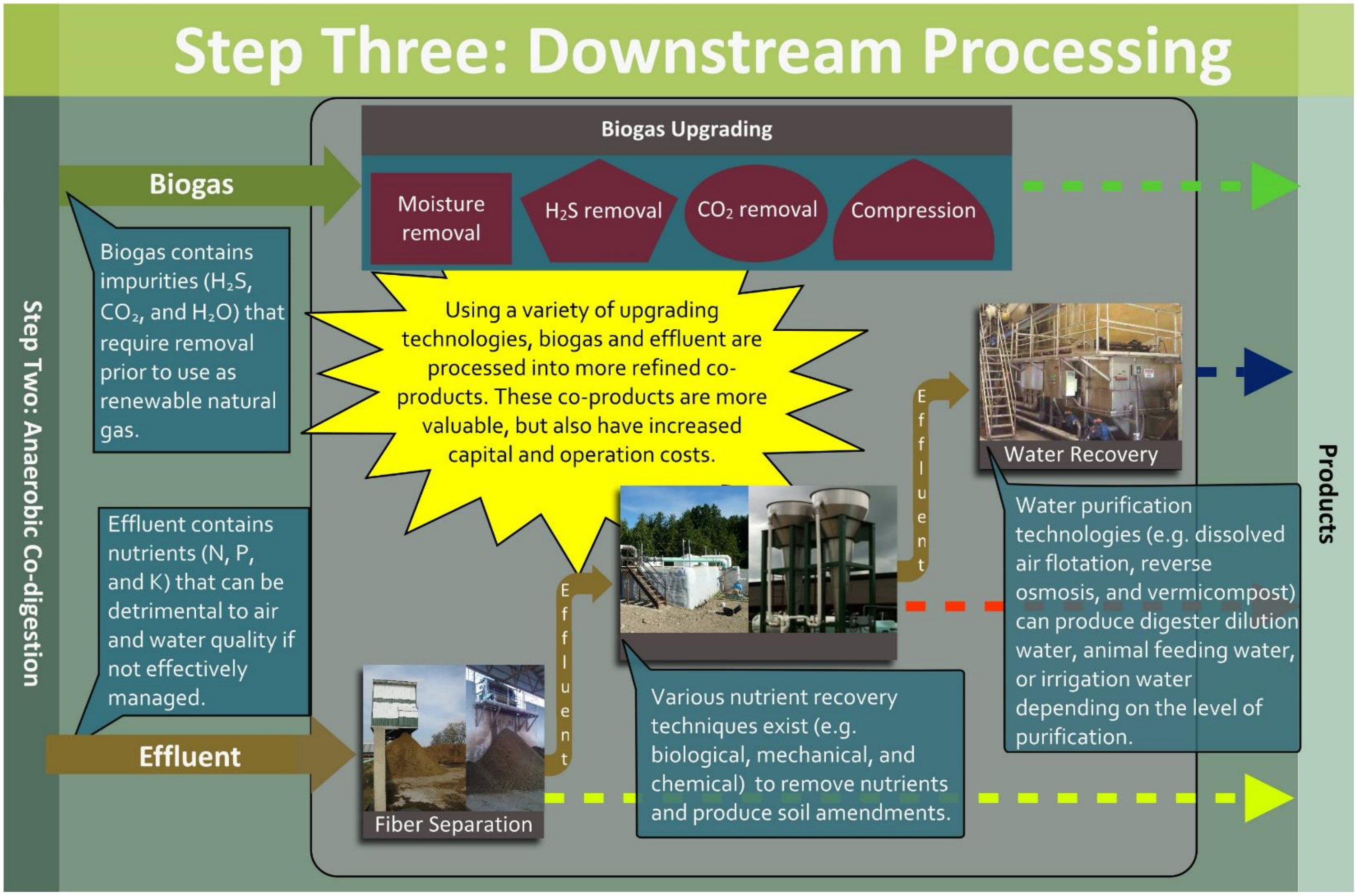

Figure 4. Downstream processing steps. Graphic by Nicholas Kennedy and Jingwei Ma. Photos courtesy of DVO Inc., Regenis, Jim Jensen, and Keith Bowers.

When the project economics are favorable, the bio-refinery can utilize additional treatment technologies downstream of the AD (Figure 4) to produce one or more value-added products (Figure 5). The economics of a variety of bio-refinery components can be further explored in *The Anaerobic Digester (AD) System Enterprise Budget Calculator* (Astill and Shumway 2016b), developed in the Pacific Northwest and intended for dairy AD. The publication *Completing a Successful Feasibility Study for an Anaerobic Digestion Project* (Jensen et al. 2018) contains additional insights about the features of a feasibility study unique to dairy bio-refineries.

Additional processing steps can also improve sustainability by further reducing the dairy's carbon footprint, producing renewable products that replace non-renewable ones, improving nutrient management, and reclaiming water for other uses. Four general categories of downstream processing can be carried out: biogas upgrading, fiber separation and processing, nutrient recovery, and water recovery. Because different processing technologies generate different products, the specific products shown in Figure 5 are examples of what can be produced within a bio-refinery context.

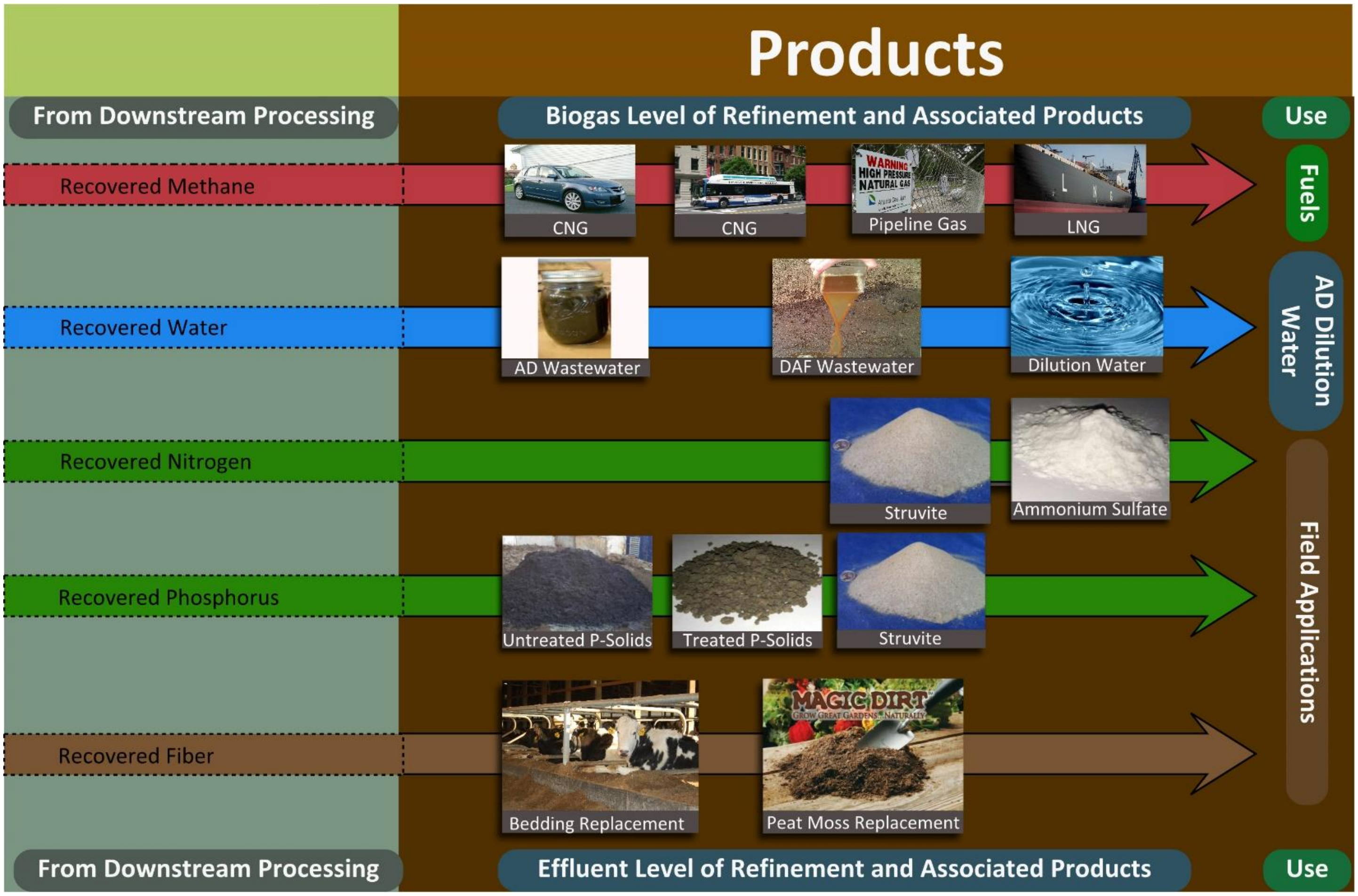

Figure 5. An assortment of products, including many not pictured here, can be produced in the dairy manure bio-refinery, depending on the specific technologies used. Graphic by Nicholas Kennedy; photos courtesy of Jason Spaceman, Jason Lawrence, John S. Quarterman, Jens Schott Knudsen, Craig Frear, DVO Inc., Cedric, Keith Bowers, Regenis, and Magic Dirt.

Biogas Upgrading

Biogas produced from the AD of dairy manure consists of approximately 55–70% methane (CH_4), 30–45% carbon dioxide (CO_2), and small amounts of hydrogen sulfide (H_2S) (300 to 4,500 ppm) and water vapor (Liebrand and Ling 2009). Methane contains energy while carbon dioxide is mostly inert, and hydrogen sulfide and water can be problematic because they are corrosive to engines. In a bio-refinery, biogas can be purified to remove water vapor, H_2S, CO_2, and other impurities suitable for higher value use as a renewable transportation fuel (Figure 4). Biogas purification technologies use a combination of mechanical, chemical, and biological approaches. More detailed information is available in *Biogas Upgrading on Dairy Digesters* (Kennedy et al. 2015b).

At present, a combination of low electrical prices and potential credits for producing upgraded biogas as a transportation fuel is pushing many bio-refinery AD projects towards production of pipeline quality renewable natural gas (RNG) (Harsch 2017; Coppedge et al. 2012). RNG is chemically identical to compressed natural gas (CNG) or pipeline quality natural gas and can be compressed and trucked to CNG filling stations for use in dedicated fleets (e.g., delivery trucks, police vehicles, buses), piped and injected into natural gas pipelines, or condensed into liquefied natural gas (LNG). Because of its environmental benefits, RNG is eligible to obtain credits in the form of renewable identification numbers (RINs) and low carbon fuel standard (LCFS) offsets for states like California (CARB 2017). RIN and LCFS credits can have a powerful positive impact on AD project economics—though their prices can also fluctuate due to market instability (Coppedge et al. 2012). For more information on how RNG can impact the economics of AD projects, refer to *Anaerobic Digester Project and System Modifications* (Galinato et al. 2015) and Astill and Shumway (2016a).

Of the estimated 205 dairy-based digester projects operating in mid-2018, only eight were upgrading biogas to RNG, although several other projects were in various stages of development (U.S. EPA Agstar 2018). Moving forward, continued interest and actual development of RNG projects will hinge on stability of credit markets, including federal RFS RINs and state level efforts. Meanwhile, barriers to adoption include the need for pipeline access as well as high capital costs due to infrastructure upgrades for gas cleaning, compression stations, fueling stations, and pipeline connections or upgrades. For those who may look to utilize the fuel for their own trucking fleet to avoid the need for pipeline access, the need for extensive vehicle modifications is also an important barrier.

Because the economics of RNG are heavily impacted by policy incentives, the possibility that these incentives could change is also important. There has been recent discussion of the potential for future credit pathways, such as RFS eRINs, which allows for crediting of renewable fuel through production of electricity specifically used for electric vehicle fueling, and such a move could spur development of more new electricity-producing projects. This could be particularly beneficial for projects that are far from pipeline access points or have other substantial barriers to making RNG economically viable.

Fiber Separation

The AD effluent is typically separated into fiber and liquid fractions via solid-liquid separators. Solid-liquid separators come in a variety of different configurations, including slope screens and screw presses, with a host of sequential operations, mesh sizes, and dewatering apparatuses (Jensen et al. 2016). Figure 6 shows a series of sequential slope screens located at a dairy digester in Jerome, ID. The process does recover some nitrogen (N) and phosphorus (P) nutrients along with the fiber, but recovery is limited compared with technologies specifically aimed at recovery of nutrients (Drosg et al. 2015; Frear et al. 2018).

After separation, fiber can be used as bedding for livestock without additional processing. It can also be aerobically treated by composting, or further processed into value-added products (Figure 7). Most dairies with AD use fiber as a livestock bedding replacement. However, many dairies are also treating fiber so that it can be used as a soil amendment or peat moss replacement, based on the product’s superior water- and air-holding capacity (Goldstein 2014; Pelaez-Samaniego et al. 2017). Because peat moss is a non-renewable resource and its mining impacts the climate negatively, an AD-fiber peat moss replacement product can improve sustainability. Other uses of the fiber that are of interest include engineered products and fuel production, though there are few dairy digesters actively producing these products currently. Technologies for processing fiber solids are covered in more detail in *Digested Fiber Solids: Methods for Adding Value* (Jensen et al. 2016).

Figure 6. (A) AD fiber processing facility under construction (AA Dairy, Jerome, ID) and (B) the same facility after construction of building cover and beginning of operation. Photos courtesy of Regenis.

Figure 7. Close-up of separated AD fiber (left). Two major uses include as animal bedding (center) and as an ingredient in retail soil amendment (right). Photos: Craig Frear, DVO Inc., and Magic Dirt (left to right).

Nutrient Recovery

Once fiber is removed, the remaining effluent stream is liquid rich in nutrients, containing N, P, and K as well as considerable amounts of suspended solids. In contrast to land application that occurs in a traditional digester context, a bio-refinery uses one or more advanced technologies to recover N, P, or K in more concentrated form. Various nutrient recovery technologies exist (Figure 8), each with its own set of removal efficiencies and capital and operation costs (Drosg et al. 2015; Frear et al. 2018).Capital and operating costs remain high for most of these technologies, so far precluding wide-scale adoption in the US. However, some early adoption is occurring for individual technologies, particularly those aimed at suspended solids and phosphorus recovery (e.g., centrifuge, polymer flocculation). Nitrogen control technologies such as ammonia stripping, nitrification/denitrification, and systems that produce water suitable for reuse), such as reverse osmosis membranes and distillation, are also of considerable interest in some areas of the country (Frear et al., forthcoming). Interest in these technologies is being driven largely by the opportunity they provide to facilitate better management of nutrients, with important possibilities for improving agriculturally-linked phosphorus eutrophication, nitrate pollution, and ammonia losses in watersheds with concentrated numbers of dairy cows. If nutrient trading, exchange mechanisms, or similar policies are adopted in this future, this could help offset the capital and operating costs and drive adoption (Frear et al., forthcoming).

For more information on the benefits and current barriers to nutrient recovery, see *The Rationale for Recovery of Phosphorus and Nitrogen from Dairy Manure* (Yorgey et al. 2014), *Approaches to Nutrient Recovery from Dairy Manure* (Frear et al. 2018) and *Economic Feasibility of Anaerobic Digester Systems with Nutrient Recovery Technologies* (Galinato et al. 2017).

Products from these systems vary substantially depending on the technologies used. Figure 9 shows some examples, including as-produced fine solids from a polymer flocculation system, an air-dried version of those same solids, crystallized struvite product, and dried ammonium sulfate crystals from ammonia stripping (left to right, respectively). Beyond the visual differences, they vary in other important ways, including nutrient density, potential for organic certification, size uniformity, and food safety pathogen treatment. Such factors can have important impacts on market viability and price. In some cases, additional post-processing (e.g., drying, pelleting, and pasteurization) may be needed to address these issues, but these can be expensive, requiring additional equipment for drying, composting, thermal char production, pelleting, or granulation.

These concentrated products reduce transportation costs compared to AD effluent and untreated manure. This facilitates application to more distant fields, which can improve nutrient management and reduce costs. It also could improve the potential for off-dairy sales, resulting in application to croplands in need of nutrients. In one bio-refinery case, the primary manure products are dosed with external minerals in a large-scale fertilizer plant, yielding a concentrated product at a nutrient density and scale that that appeals to large-scale agriculture (Midwest Bioag 2017).

When these biologically-derived soil amendments are used in place of energy-intensive synthetic fertilizers, they indirectly reduce the farm's carbon footprint. In some cases, they also supply an important source of organic carbon and secondary or micronutrients that can benefit soil health.

Figure 8. Numerous nutrient recovery technologies are currently being tested on dairies at pilot and commercial-scale. Shown here are a struvite crystallizer (upper left, photo courtesy Keith Bowers), a dissolved air flotation system (upper right, photo courtesy Regenis), an ammonia stripping system (lower left, photo courtesy Biosis), and a reverse osmosis membrane system (lower right, photo courtesy Regenis).

Water Recovery

To enable proper functioning of both the dairy's manure management system and the digester, dairy manure is often diluted with fresh or reused water to achieve desired total solids levels prior to digestion. Recovering water from downstream processes and recycling it for dilution can conserve a limited and valuable resource, reduce the costs of fresh water inputs, and reduce storage, hauling, and application costs for disposal of the effluent. Additionally, improved quality such as by removing suspended solids can also benefit some application methods (e.g., pivot, drip irrigation) and lead to significant savings in odor and nutrient management during application (Zeb et al. 2017).

The desired end use for the water dictates the degree of purification needed (Figures 10 and 11). For example, for water to be recycled for use as dilution water prior to AD, the bulk of suspended solids needs to be removed, along with potential inhibitors to the AD process, such as ammonia and some salts. For intensive volume reduction, reverse osmosis membrane systems can produce a water that can be discharged to US waterways, through removal of pathogens and salts, although often costly and difficult local discharge water regulations must be met.

Figure 9. From left to right: wet as-produced fine solids from polymer flocculation (4.5:3.8:1); dried version of the same product (3:3:1); struvite crystals (6:29:0:16Mg); ammonium sulfate crystals (21:0:0:24S). N, P_2O_5, K_2O dry weight fertilizer value in parentheses. Photos courtesy of Regenis, Craig Frear, Keith Bowers, and Craig Frear (left to right).

Figure 10. Various technologies exist to purify water. The dissolved air flotation (DAF) unit in Reynolds, IN (left) generates water that can be re-used within the AD system after ammonia stripping. A reverse osmosis unit in Webberville, MI (right) generates water that can be used as AD dilution water, animal drinking water, or stream discharge. Left photo courtesy of DVO Inc., right photo courtesy of McLanahan Corporation.

Possible Future Developments

As the bio-refinery concept is further developed, it is almost certain to include technologies not covered in detail here. Examples of possible future directions include the potential integration of advanced thermal treatment, such as pyrolysis, hydrothermal carbonization, or even gasification to yield additional renewable energy from dry, lignocellulosic material (Pelaez-Samaniego et al. 2017). Under these models, there is potential for co-treatment of biogas and produced syngas. Chars could also be produced, with the potential to be used within the bio-refinery platform for gas and nutrient treatment or sold as a value added product (Pelaez-Samaniego et al. 2017). Chemical platforms could also be used to short-circuit classical AD biology and produce valued chemicals (e.g., organic acids, alcohols, and polymers) or convert biogas to liquid fuels (Arslan et al. 2016; Budzianowski 2016).

Power-to-fuel technologies could also play an intriguing future role in animal bio-refineries (Götz et al. 2016; Ghaib and Ben-Fares 2018). This concept has been developed in response to the fact that as renewable wind and solar energies have represented an increasing proportion of energy supply, moments of over-supply to the electricity grid become more likely. Within a power-to-fuel framework, excess power could be transmitted to a dairy digester project, where the power would be converted to hydrogen gas. Hydrogen gas could be combined with the carbon dioxide in the existing biogas to simultaneously scrub the biogas of carbon dioxide impurities and increase methane or RNG production. The dairy bio-refinery would thus serve

Figure 11. During water purification, raw manure wastewater is sequentially treated. Photos show raw manure (a), after digestion and primary solids separation (b), and after DAF treatment (c). After treatment with reverse osmosis membranes, discharge water appears clear (d). Photos courtesy of Craig Frear.

as both an intensified RNG producer and as baseload balance to the grid.

These are but just a few technological possibilities for future dairy-based bio-refineries, and only time will make clear which, if any, will ultimately be viable within a dairy context.

Conclusion

Multiple add-on technologies exist for transforming manure-only digesters into dairy manure bio-refineries. This publication highlights some of the more important and common add-on technologies in use on dairies as of 2018. In addition to the possibility of future technological development, three important factors that will influence adoption of bio-refineries are scale, co-product market development, and policy.

Presently, one of the most advanced dairy-based bio-refineries resides at Fair Oaks Farms and Prairie's Edge Dairy in Indiana, home to tens of thousands of cows, indicating the scale at which implementation of these more advanced, multiple bio-refinery concepts is occurring. This facility integrates many of the technologies discussed, including a core anaerobic digester, biogas upgrading to RNG for fueling their milk truck fleet, fiber and fine solids separation, and subsequent upgrades and sales of these solids, including a dedicated fertilizer plant for production of a high nutrient density fertilizer from the manure-based organic core (Figure 12). In addition to these components, the facility has a public education facility relating to the bio-refinery approach. While this installation is impressive, it is important to note that even at this larger scale, a bio-refinery approach adds complexity alongside capital and operating costs. Therefore, it will likely take some time to validate the emerging models and spur adoption even for larger dairies. Over time, wider adoption may also stimulate modified models that are appropriate for smaller scale dairies.

An important challenge for early adopters of bio-refinery models is that co-product markets are only now being solidified. Developing markets will take time and overcoming this will be important to reducing risk and catalyzing adoption by other dairies. Policy development may also be an important factor for encouraging wider adoption, through mechanisms such as nutrient trading, bio-based fertilizer incentives, and public capital investment grants.

Figure 12. Prairie's Edge Dairy digester gas upgrading, Fair Oaks, IN. Image courtesy of Mark Stoermann.

Meanwhile, even limited deployment of the bio-refinery model on dairies is contributing to enhanced sustainability, including ameliorating issues associated with excess nutrients, replacing finite natural resources with renewable substitutes, reducing the climate impacts of dairies by capturing and destroying methane (a powerful GHG), and in some cases, conserving water. While these advantages are being realized across the country, we have estimated the climate benefits provided by operational dairy bio-refineries in Washington State to illustrate how these contributions might be quantified (see sidebar *Contributions of Washington Dairy Bio-Refineries to Mitigating Climate Change* for details). A full bio-refinery mitigates GHG emissions by providing biologically-based alternatives to GHG-intensive products, such as fertilizers, while also offsetting carbon emissions associated with fossil fuel use through renewable energy generation.

As of late 2017, there were eight operational dairy bio-refineries serving an estimated 16,548 cows in Washington State. The total current mitigation benefit was estimated to be 0.12 million metric tons of carbon dioxide equivalents annually, representing 2% of Washington State's goal of reducing its emissions by 6 MMT by 2020 (reductions are calculated based on 2013 emissions, the most recent year for which data was available) (Washington Department of Ecology 2016). Given that bio-refineries are currently serving just 6% of the state's dairy cows (USDA NASS 2017), in the absence of statewide climate policy, this number indicates a potential for more substantial future contributions if technological and policy innovations continue.

Contributions of Washington Dairy Bio-Refineries to Mitigating Climate Change

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Dairy cattle create direct and indirect emissions of greenhouse gases (GHGs) throughout the production process, including from enteric fermentation (the animals' digestive process), manure management, and after application of manures to soils (US EPA 2017a). There is significant variation in emissions from manure, depending on the type of management system employed, with higher methane emissions originating from liquid manure management systems. These liquid manure systems are increasingly used in dairy operations (US EPA 2017a), leading to recent increases in GHGs associated with manure management. In total, manure management for dairy cattle in the US contributed an estimated 49% of the GHG emissions associated with manure management for all livestock and poultry in 2015, and an estimated 0.48% of gross GHG emissions in the United States (US EPA 2017a). (In absolute terms, manure management accounted for an estimated 34.8 million metric tons of carbon dioxide equivalents, CO_2e, in 2015.)

Dairy bio-refineries in Washington reduce GHG emissions in several ways, with the largest contributions coming from the capture and destruction of methane, and from generating renewable energy (Table 1). Those bio-refineries that also generate biologically-based alternatives to GHG intensive products provide smaller, but real, additional mitigation benefits. Because data did not allow for an accurate estimation of co-digestion rates at dairy digesters in Washington State, benefits from fertilizers were calculated at a relatively low 5% co-digestion rate, and a higher 20% co-digestion rate. Further details of the analysis are provided in Appendix 1.

Table 1. Summary of greenhouse gas mitigation from eight operational Washington State dairy digesters. These digesters served an estimated 16,548 cows as of late 2017. Benefits from fertilizers were calculated at a relatively low 5% co-digestion rate, and a higher 20% co-digestion rate.

		Total Annual GHG Mitigation	**GHG Mitigation Per Cow**
		MMt CO_2e/yr	Mt CO_2e/cow/yr
AD Methane Capture		0.06	3.88
Electrical Offset		0.03	1.52
Peat Replacement Using Separated Fiber		0.005	0.31
Fertilizer Equivalents at 5% Codigestion			
	Phosphate	0.00025	0.02
	Nitrogen	0.02	1.34
Fertilizer Equivalents at 20% Codigestion			
	Phosphate	0.00029	0.02
	Nitrogen	0.03	1.59
	Total at 5% Codigestion	0.12	7.07
	Total at 20% Codigestion	0.12	7.32

Acknowledgements

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Appendix 1

Estimating the Contributions of Washington State Dairy Bio-refineries to Mitigating Climate Change

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Table 1, reproduced here for convenience, represents estimates of the annual GHG emissions reductions provided by extant dairy AD installations in Washington State as of late 2017. The number of cows contributing to each digester was estimated through knowledge of dairy operations (Dr. Craig Frear, personal communication); when actual numbers were not known, calculations of wet cow equivalents (WCEs) were based on the Washington State Department of Agriculture's 2017 Dairy Farm Inventory (WSDA 2017). Total number of cows used for subsequent calculations is 16,548.

Actual electricity produced was obtained largely through data obtained from electrical utilities. Given the reliance on actual electricity data, enhanced energy production generated through co-digestion is already captured. However, given that co-digestion rates were not known, two potential co-digestion rates of 5% and 20% were considered in the fertilizer section so as to capture additional nutrient loading. When operated under a permit exemption, co-digestion at dairy digesters is limited to 30% or less in Washington State (Yorgey et al. 2011).

Table 1. Summary of greenhouse gas mitigation from eight operational Washington State dairy digesters. These digesters served an estimated 16,548 cows as of late 2017. Benefits from fertilizers were calculated at a relatively low 5% co-digestion rate, and a higher 20% co-digestion rate. When operated under a permit exemption, co-digestion at dairy digesters is limited to 30% or less (Yorgey et al. 2011).

		Total Annual GHG Mitigation	GHG Mitigation Per Cow
		MMt CO_2e/yr	Mt CO_2e/cow/yr
AD Methane Capture		0.06	3.88
Electrical Offset		0.03	1.52
Peat Replacement Using Separated Fiber		0.005	0.31
Fertilizer Equivalents at 5% Codigestion			
	Phosphate	0.00025	0.02
	Nitrogen	0.02	1.34
Fertilizer Equivalents at 20% Codigestion			
	Phosphate	0.00029	0.02
	Nitrogen	0.03	1.59
	Total at 5% Codigestion	0.12	7.07
	Total at 20% Codigestion	0.12	7.32

Constituent production rates per cow (VS, N, and P lb/cow/yr) were based on the American Society of Agricultural Engineers (ASAE), Standard D384.2 (2005). These were used in calculating AD Methane Capture (Table 1) in conjunction with the US EPA's estimate of methane production (0.24 m^3/kg VS) and methane conversion factors for manure management systems (US EPA 2017a). For the dairies in question, the type of manure management system of each dairy was identified (Dr. Craig Frear, personal communication); the dairies in Washington State are offsetting GHG emissions from primarily Liquid Slurry and Anaerobic Lagoon applications. Methane emissions were converted to MT CO_2e/yr using the EPA equivalency calculator (US EPA 2017b) .

Total 2016 contributions made to the public electricity utilities (Electrical Offsets; Table 1) were determined through personal communication with Puget Sound Energy (Tyler O'Farrell , personal communication), Snohomish County PUD (Doug O'Donnell, personal communication), and a feasibility study conducted by WSU for one of the digesters (Coppedge et al. 2012).

Offsets due to peat substitution in landscaping applications were calculated based on estimates of fiber production per animal per year (9 m^3), moisture content (75%) density (401 kg/m^3) and percent used on-farm (50%) to determine a total MT/yr of dry matter used as peat replacement. Conversion to offsets was based on 0.69CO_2e produced per ton of peat (Cleary et al. 2005).

Fertilizer offsets were based on N and P production rates per cow per year and two co-digestion scenarios as aforementioned. The amount of N and P contributed as a consequence of co-digestion was estimated to be 6.45 kg/yd^3 and 0.8 kg/yd^3, respectively, based on a range of scientific studies of food waste digestion (Liang Yu, personal communication). The total amounts of manure per cubic yard and consequent N and P produced by the dairy cows were calculated using ASAE production rates; the contribution of nutrients made by two co-digestion scenarios were then evaluated. In the first, 5% additional volume of food waste was assumed digested with the manure, and the additional nutrient loading was estimated through the aforementioned values. In the second, 20% additional volume was assumed to be co-digested. Total kg/yr of N and P digested, manure and food waste, were calculated and converted to synthetic N and P fertilizers; a one-to-one organic-to-synthetic N was assumed; however, total organic P produced by the cows in this study was converted to P_2O_5. The conversion of N and P to synthetic fertilizer CO_2e offsets was conducted by applying a multiplier of 7.67 (N) and 1.17 (P) CO_2e potential/kg fertilizer to the total mass of nutrients loaded to the digester (Insam and Wett 2008).

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (GREET, Version 1.3.0.13239, 2017) and the Climate Action Reserve US Livestock Project Protocol (Organic Waste Digestion Project Protocol, Version 2.1, 2014) were evaluated to ensure relative continuity between those methods and this study. Unlike the GREET model, this study does not consider methane emissions due to AD equipment leakage, nor does this study include methane emissions as a consequence of decomposition of land applied digested manure. However, the GREET model uses EPA and IPCC values similar to those used in this application. The Climate Action Reserve Model also references EPA and IPCC values to use in calculating GHG offsets based on data accumulated for a specific project. We feel therefore that the results of this effort are commensurate with those that would be obtained using either of the other models.

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