Appendix C

Review of Technologies Potentially Applicable to Agricultural Symbiosis Projects in Washington State
1. Overview

This Appendix presents the results of a literature review that was conducted to explore technologies that might be applicable to agricultural symbiosis projects in Washington State. After an overview of the agricultural waste availability in Washington State, the technologies potentially applicable to agricultural symbiosis projects in Washington State are reviewed and compared.

The reviewed technologies include gasification, pyrolysis – including slow pyrolysis and fast pyrolysis – anaerobic digestion, hydrothermal liquefaction, composting, biochar production and use, compost blending, vermicomposting, larva-based composting, and vermicomposting. These technologies have different technology readiness levels (TRLs): while some technologies are already commercially available, others are still at R&D levels. For example, biogas via anaerobic digestion has been produced in Washington State for several decades. More recently, the introduction of low-carbon fuel standards (LCFS) has drawn more attention to projects for the conversion of biomass into Renewable Natural Gas (RNG). These projects are already being implemented and are considered low risk.

This review highlights and compares the main advantages and disadvantages of each technology and identifies short and long-term strategies to promote agricultural symbiosis projects in Washington State. After the initial technology review, this study analyzes more in detail the Anaerobic Digestion (AD) process, biogas, and Renewable Natural Gas (RNG) production, current and potential RNG production in Washington State, and economic and environmental impacts of RNG. An example of an agricultural symbiosis project using anaerobic digestion in Washington State is presented and its potential economic and environmental benefits are discussed.

2. Introduction

The agricultural sector contributes considerably to Washington's economy and society. It generates a rich diversity of food, fiber, forage, and fuel for the state, and provides income and employment on over 35,000 farms in all 39 counties. Top five commodity groups in Washington agriculture in 2021 were: fruits and berries (39.3%), cattle and dairy (23.8%), grains, oilseeds and legumes (11.0%), hay and other crops (10.3%), vegetables and potatoes (9.9%) [1].

Agriculture requires large areas of land for its productive activities. About one third of the land area of Washington, corresponding to 15 million acres, is classified as agricultural, another one third as forest land, and the remaining one third is public land owned by federal or state governments. Washington agriculture has evolved in response to a changing market and the capabilities of the diverse ecosystems in the state. There are major differences in the productive potential of the coastal climate of Western Washington, the irrigated areas of Central Washington, the dryland (rain-fed) agriculture of Eastern Washington, and the range of varying elevations throughout the state [2].

In 2008, the Washington legislature set ambitious goals for reducing greenhouse gases (GHGs) [3]. Based on the most recent scientific findings, Washington State Department of Ecology recommends expanding these goals:

- Reduce statewide GHGs to 1990 levels by 2020.
- Reduce statewide GHGs to 25% below 1990 levels by 2035 (Washington State Department of Ecology recommends expanding this goal to a 40% reduction below 1990 levels).
- Reduce statewide GHGs to 50% below 1990 levels by 2050 (Washington State Department of Ecology recommends extending this goal to an 80% reduction below 1990 levels).

The 2023 Farm Bill or Agricultural Resilience Act (ARA) includes a set of goals for farmers to help mitigate climate change and increase agricultural resilience, starting with the overarching goal of reaching net zero greenhouse gas emissions from U.S. agriculture by no later than 2040 [4].
According to the US Code Title 7, Section 3103, "Sustainable Agriculture" is defined as “an integrated system of plant and animal production practices having a site-specific application that will, over the long-term, satisfy human food and fiber needs; enhance environmental quality […] make the most efficient use of nonrenewable resources and on-farm resources and integrate, where appropriate, natural biological cycles and controls; sustain the economic viability of farm operations; and enhance the quality of life for farmers and society as a whole.”

This Appendix will analyze technologies for the use of waste resources in agricultural symbiosis projects. Successful symbiosis projects offer both a compelling business case for each participating entity and deliver substantial sustainability performance improvements [5]. It is important to note that the use of waste resources should be considered after efforts have been made to reduce and avoid waste, and reuse, recycle, and compost waste where possible. The top of the hierarchy (waste reduction/avoidance) identifies the most preferred and sustainable option, with the least preferred option being waste disposal/release [6].

3. Agricultural Waste Resources in Washington State

3.1 Food Waste

Food waste is defined by Bioenergy Technologies Office (BETO) within the Department of Energy (DOE) as “food not used for its intended purpose, no longer fit for human or animal consumption, and sent for disposal. Byproducts from food and beverage processing that cannot be recycled or reused are also in this category” [7]. The U.S. Department of Agriculture estimates that food losses represent 31 percent of food produced in the United States [8],[9]. Fruit and vegetables are especially prone to losses at these stages due to their perishability. Nearly 40 percent of losses in fruits and vegetables throughout the supply chain occur prior to the retail or consumer stage. Food loss represents significant loss of money and other resources invested in food production, including land, fresh water, labor, energy, agricultural chemicals (e.g., fertilizer, pesticides), and other inputs.

Washington State generates an estimated 1,200 to 1,350 pounds of organic waste per person per year. Approximately half of food waste is landfilled with most of the remainder either being composted or incinerated [10]. While putting these waste materials in landfills can cost $100 or more per ton, processing these materials into renewable energy and other beneficial co-products can spark new economic activity [3].

3.2 Animal Manure

Milk is the second largest agricultural commodity in Washington, contributing more than $1.1 billion in farm gate revenue. In 2017, the Washington Department of Agriculture (WSDA) identified 144 small dairies in the state. While the number of dairies continues to decline, the total number of mature cows in Washington has stayed at roughly 275,000 head. Milk cows produce large volumes of manure and wastewater, most of which is stored in lagoons during wet months. Liquid manure storage releases methane equivalent to 4 to 5 tons of CO₂ for each cow per year. Manure can also end up in the water streams when storage structures leak or overflow.

As a mitigation strategy, animal manure can be applied to agricultural lands as a fertilizer, enabling farmers to reduce the amount of chemical fertilizers used on agricultural lands. However, rainfall events that follow manure land application may lead manure to enter water streams and run into waterbodies. Manure nutrients can exacerbate eutrophication of surface waters, a phenomenon caused by too many nutrients in the water, leading to algal growth and then decomposition, which reduces oxygen levels in the water below those required by aquatic organisms such as fish.

In recent years, the United States has experienced a shift from large numbers of small-scale livestock farms to larger-scale sites
holding high amounts of livestock in a small land area, referred to as concentrated animal feeding operations (CAFOs). CAFOs produce large amounts of animal manure in small land areas. Therefore, standards are enforced to prevent CAFOs from discharging and handling manure nutrients (predominantly nitrogen and phosphorous) in harmful ways for the environment. Several counties in the United States have been identified as having more manure-supplied nutrients than crops need. As farms have become more specialized, they have also separated animal and crop production [11]. Thus, there exists a limited demand for manure as a commercial fertilizer replacement as determined by nearby cropland.

3.3 Fats, Oils, and Greases

Fats, oils, and greases (FOG) include animal byproducts and grease from food-handling operations, and it is typically processed at rendering companies for use in various industries. Three distinct materials are produced from these operations: yellow grease (i.e., filtered used cooking oil), animal fats (i.e., tallow, white grease, and poultry fat), and brown grease (i.e., rendered trap/interceptor grease). Animal fats and yellow grease are conventionally managed by large scale meat-rendering operations [7]. FOGs are typically used to produce biodiesel, and more recently renewable diesel and sustainable aviation fuels although some amounts are disposed of at landfills or incinerated.

3.4 Sewage Sludge

The treatment of wastewater produces solid residuals commonly referred to as sludge. Sludge is mainly composed of organics with some inorganic solids. The treatment of sludge in wastewater plants produces nutrient-rich organic materials known as biosolids. In the United States, about half of fully treated sludge is land applied as a fertilizer while most of the remaining material is incinerated or sent to a landfill. 40 CFR Part 503 establishes standards, including general requirements, pollutant limits, management practices, and operational standards for the final use or disposal of sewage sludge.

There are regions in California where there are no landfills that accept biosolids for disposal [12]. Similarly, the Washington State Department of Ecology classifies biosolids as a beneficial resource and requires wastewater treatment facilities to keep biosolids out of landfills [13].

For incinerated sludge, EPA has defined criteria for which plants are required to implement certain emissions management practices. Therefore, more biosolids incinerators are being taken out of commission nationally than are being constructed. Finally, the Washington State Department of Ecology does not consider incineration to be a beneficial use of biosolids [14]. All incinerators are required to maintain records of emissions for a five-year period, and large sludge management facilities are required to submit an annual report. In addition to EPA permits for sludge, air emissions are regulated under the Clean Air Act and may require further permits.

3.5 Wet Waste Feedstock Prices

Badgett et al. (2019) estimated prices for the resources: food waste, fats, oil, and greases (FOGs), animal manure, and sewage sludge [15]. The study relates the resource price to the avoided cost of disposal through current waste management options such as landfilling. The study shows that significant amounts of these feedstocks could be available at negative prices, meaning that a potential bioenergy facility could receive these materials for free or be paid to accept them. For example, sewage sludge exhibits prices from about -$125 per Mg to greater than $10 per Mg, depending on the cost of the sludge disposal alternative used. Several techno-economic studies assume a tipping fee (also referred to as a feedstock credit) that a bioenergy facility would charge to accept a waste material. Changes in current and future regulations may significantly impact the economics of using wet waste feedstocks.
4. Review of Technologies for the Valorization of Agricultural Waste

Technologies for the valorization of agricultural waste convert waste material into heat, electricity, fuel, fibers, or chemicals through various processes. In this section, the following technologies are reviewed and compared: gasification, pyrolysis—including slow pyrolysis, fast or flash pyrolysis, anaerobic digestion, hydrothermal liquefaction, composting, biochar and compost blending, vermicomposting, larvae-based composting, and vermifiltration. Agricultural waste resources considered herein include food waste, animal manure, sewage sludge, and FOGs.

4.1 Gasification

Gasification is a thermochemical process that converts biomass into more concentrated forms of potential energy in a multistep process. Gasification essentially uses air, oxygen or steam to convert dry or wet feedstock into gases, such as carbon monoxide, carbon dioxide, and hydrogen, leaving behind a char byproduct [16]. The process includes pyrolysis (i.e., heating without air to make charcoal, or biochar, and “tar” gases) and reduction (i.e., converting cracked tar gases to hydrogen gas). Biomass entering the system must be as dry as possible to maximize overall efficiency of the process. Typically, only feedstocks with less than 30-50% moisture content are viable for gasification, with most gasifiers preferring feedstocks with 10-30% moisture content. Gasification’s final product is a low-energy fuel that can be burned directly or used in gas engines. If it is cleaned significantly, then the fuel can be turned into synthesis gas (i.e., syngas) which is commonly used in methanol, ethanol, fertilizer, hydrocarbons, and electricity production [17].

For dry gasification systems, uniformity of particulates is highly important to temperature propagation rates; therefore, some type of pelletization grinding, or blending, is necessary prior to use in thermochemical conversion. Additionally, feedstocks must be free of contaminants that can cause the thermochemical system to clog or render the operation ineffective by reducing peak temperatures. Ash found in waste may contain alkaline salts and other metals. Although the ash is removed frequently throughout the conversion process, melted or vaporized salts can combine with silica in dry gasification processes to form a sticky and highly mobile substance that blocks air flows and coats catalytic sites. This material would reduce temperatures in the process and affect gas quality.

4.2 Pyrolysis

Another thermochemical conversion process, pyrolysis—converts biomass into solid (charcoal), gaseous (fuel), and liquid (bio-oil) forms. It involves heating biomass up to 350-550 C in the absence of oxygen, converting the organic portions of feedstocks into volatile gases and condensable tars and forming pyrolytic oil or bio-oil. The amount of charcoal, gas, and bio-oil is affected by temperature, rate, and time of the process [11].

**Slow Pyrolysis.** Slow pyrolytic processes use relatively lower temperatures (350-450 C) and longer residence times to encourage solid production. The main product of slow pyrolysis is biochar, a solid product characterized by high carbon content and porous structure with large surface area [10]. Biochar is an appealing product for use in industrial and agricultural contexts because it readily adsorbs chemical compounds. It also shows promise as a means for carbon sequestration when applied to soils.

As outlined in Amonette et al. (2016a, b), production of biochar from waste wood in Washington State using modified biomass boilers has the potential to yield many benefits, including improved biomass productivity, decreased irrigation costs, and, perhaps most importantly, drawdown of atmospheric carbon dioxide [10], [18].

Typical feedstock streams used in slow pyrolysis include agricultural crop residues (straw from cereal crops), residual forest biomass from timber-
harvesting operations, wood reclaimed from municipal solid waste (dimensional lumber, engineered wood, pallets and crates, natural wood, and other non-treated wood), and green waste also reclaimed from the municipal solid waste stream. When using wet feedstock, energy consumption is particularly significant. Dewatering feedstocks before pyrolysis helps to reduce energy consumption.

**Fast Pyrolysis.** An alternative to slow pyrolysis is fast pyrolysis. Compared to slow pyrolysis, fast pyrolysis has shorter residence times (1-2 seconds) and burns at temperatures of 450-550 °C. The main product of fast pyrolysis is bio-oil. This process has a reported yield of 60-70 percent [19]. The use of bio-oil directly in engines or turbines is not recommended given the high-water content (typically 15-50 percent) and high oxygen content in the oil, which makes it unstable and acidic. However, the fuel blend stock may be used in an engine or turbine after upgrading (hydrodeoxygenation). The fast pyrolysis oil may also be used as a feedstock in a petroleum refinery after liquid separation or a mild hydrotreating. These additional processes add costs and complicate the process but result in a fuel blendstock that is more applicable to existing infrastructure.

### 4.3 Anaerobic Digestion

Anaerobic digestion (AD) is a process in which organic matter from wet organic wastes (i.e., liquid manure, food processing wastes, etc.) is converted into methane by bacteria in the absence of oxygen. The biogas is then collected and may be used to generate combined heat and power (CHP) or the methane in biogas separated from carbon dioxide and other trace species to make renewable natural gas (RNG). In addition to biogas, a carbon – and nitrogen-rich slurry (digestate) is also produced which may be used as a fertilizer or soil amendment. Approximately 50% of the biomass ends up in the digestate, 25% in CO₂ and 25% in CH₄.

AD is a well-established technology in Washington State, with several anaerobic digesters operating on wastewater treatment plants and food processing plants. Plant operators often burn the biogas produced to provide heat for the digester and plant facilities. Biogas also powers generators that produce both heat and electricity. Larger treatment plants can even produce surplus electricity that potentially goes onto the grid through power purchase agreements with local utilities. These larger plants can also be in a position to upgrade biogas to RNG quality that meets natural gas pipeline standards.

One of the main advantages of AD is its ability to process biomass sources with high moisture contents (less than 40% dry matter), which is contrary to many other waste conversion methods [20]. AD technology demands little energy for heating and electricity under normal conditions, so it is a highly energy-efficient process [21]. Other commonly recognized on-farm AD benefits include odor reduction, air quality improvement, greenhouse gas emissions reduction, reduction in potential pathogens from manure entering waterways, and the use of the digestate as an alternative to chemical fertilizers [22].

### 4.4 Hydrothermal Liquefaction

Hydrothermal liquefaction of biomass is the thermochemical conversion of biomass into a hydrothermal liquid oil/bio-crude which can be subsequently upgraded to liquid fuels. The wet biomass is processed in a hot, pressurized water environment for sufficient time to break down the solid biopolymeric structure to mainly liquid components [23]. HTL generates bio-crude from organic matter thanks to specific characteristics, such as the presence of water in hydrothermal conditions, with temperatures ranging from 500 to 700 K and pressures between 100 and 300 bar [24]. The process is meant to provide a means for treating wet wastes without drying by maintaining a liquid water processing medium.

Hydrothermal liquefaction produces a liquid fuel known as biocrude. Biocrude/hydrothermal oil
can be upgraded to fuel products with the use of hydrogen and a catalyst(s). The hydrothermal liquefaction process developed by Pacific Northwest National Laboratory using sewage sludge as a feedstock has created the following products: an organic biocrude phase, an aqueous phase, and small amounts of solids and gases [7]. The biocrude is upgraded at a centralized plant with the aqueous phase treated by hydrothermal gasification and off-heat used within the plant.

HTL has a number of advantages over other thermochemical conversion methods. High lipid concentrations are not required for effective HTL energy conversion and the need for energy-intensive feedstock drying is potentially reduced or eliminated because a feedstock slurry is used as an input [25]. The high-efficiency chemistry of HTL transforms almost all the biomass into biocrude oil, which largely self-separates from water as the reaction solution returns to standard temperature and pressure conditions. Further, HTL does not generate significant amounts of sludge or hazardous products of combustion such as NOx. However, some aspects of the technology are still at the R&D level.

4.5 Composting

Composting is an aerobic process that transforms organic waste via decomposition into stable organic matter, which can be used as a nutrient source and soil conditioner: a valuable downstream product for use in agriculture or other settings [10]. Composting is widely used in Washington State and throughout the U.S. to sustainably manage organics. In 2019, there were approximately 66 compost facilities in Washington State, composting a total of nearly 1.4 million tons of material [26]. The composting process is aerobic; however anaerobic conditions exist in some parts of the piles [27]. During composting, carbon dioxide (CO2) is released under aerobic conditions, while CH4 (methane), H2S (hydrogen sulfide), and N2O (nitrous oxide) are generated under anaerobic conditions.

During composting, wet waste undergoes a low-moisture digestion process that can increase its value. This biological process requires bacteria to stabilize waste's organic matter and nutrients. It shares similarities with anaerobic digestion in that it reduces the overall volume of wet waste and it reduces the number of pathogens. Composting's aerobic nature makes it simpler and less expensive than anaerobic digestion, though organic carbon is lost as carbon dioxide rather than being collected as methane [11].

4.6 Biochar and Compost Blending

Production of compost often causes odor and greenhouse gas emissions. Application of biochar from thermal processes to reduce gas emission during and after the composting process is a promising efficient low-cost solution to this problem [10].

Research suggests that blending compost with biochar, especially prior to composting, may optimize the physical and chemical properties of the resulting product. Compost provides a nutrient addition that is not provided with biochar alone, but biochar, perhaps because of its high surface area, may increase availability of nutrients added as fertilizer or compost [10].

4.7 Vermicomposting

Vermicomposting refers to a process where worms are fed manure or other waste with other low-value feedstocks such as office paper, cardboard, or vegetation and fruit waste. The worms reduce overall organic matter and produce new worms and worm "castings" (i.e., worm manure). Castings are a high-value, organic fertilizer. Although vermicomposting has been applied to multiple types of agricultural manure, it is best suited for beef manure, poultry litter, and horse bedding with optimal moisture content of the substrate being 75 percent to 85 percent.

Vermicomposting presents some disadvantages. First, prior to vermicomposting, the manure may need to have its nutrient ratio and moisture content adjusted. For example, due to its relatively high nitrogen-to-carbon ratio, poultry manure
generally requires added organic material, such as paper or cardboard, in a 4-to-1 ratio to achieve successful vermicomposting. The second disadvantage is the space needed for worm beds. A herd of 100 dairy cows would require a vermicomposting facility of 5,200 square feet, and a herd of 1,000 cows would require a vermicomposting plot of the size of a football field. The facility would likely require a roof and temperature control. Other challenges associated with vermicomposting include the operator receiving training to manage worm health, as pH, temperature, and pests and predators need to be closely monitored.

4.8 Larvae-Based Composting

In larvae-based composting, insect larvae feed on manure or other waste, grow, and are harvested prior to metamorphosis. The larvae essentially break down manure as they feed on it and, similarly to worms in vermicomposting, secrete waste free of pathogens which is considered a high-value compost [11]. Some research has explored further processing the harvested larvae into value-added products. For example, some businesses have packaged dried black soldier fly larvae and sold it as feed supplements and treats for chickens and pets. Several species of insect larvae have been used for composting manure, and many types of fly larvae can reduce manure’s organic content. Only the black soldier fly, however, is not considered a pest. Disadvantages of black soldier fly treatment include treatment system size, need for customized infrastructure to allow raw manure to be conveyed to the black soldier fly beds as soon as possible, and the cost of heating the beds. Additionally, farm operators that choose a larvae-based composting system require new training to manage larvae-based composting plants, as pH, temperature, pests, predators, and other factors need to be monitored.

4.9 Vermifiltration

Traditional vermicomposting requires manure to have a relatively low moisture content. A nonconventional system called vermifiltration treats process water from manure systems (i.e., a waste stream that has had solids removed). Vermifiltration operates like a traditional filter where water is allowed to flow over a substrate (e.g., rocks, plastic) and a bacterial biofilm degrades pollutants. Wood chips can be used as a substrate to support bacterial growth and provide a carbon source for worm growth. In this system, the bacteria consume dissolved nutrients and pollutants in the water, and the worms consume the bacteria that slough off the upper layers and drop to the bottom of the system. The wood chips, along with worm waste or “castings,” are periodically harvested and turned into commercially viable fertilizers. Unlike vermicomposting, vermifiltration has the added advantage of treating the liquid waste stream by reducing and removing dissolved constituents (particularly ammonia) via bacterial degradation. It also promotes adsorption of some materials onto the fresh organic material (i.e., wood chips) periodically added to promote healthy worm growth. Challenges associated with vermifiltration include caring for the worms and identifying secondary product markets that produce the appropriate return on investment.

Table 1 summarizes the advantages and disadvantages of different technologies for the valorization of agricultural waste. In the next sections, this study further analyzes the Anaerobic Digestion (AD) process, biogas and Renewable Natural Gas (RNG) production, current and potential RNG production in Washington State, and the economic and environmental impacts of RNG.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Advantages</th>
<th>Disadvantages</th>
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<tbody>
<tr>
<td>Casification</td>
<td>● Converts biomass into more concentrated forms of potential energy</td>
<td>● Biomass entering the system must be as dry as possible to maximize overall efficiency of the process.</td>
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<td></td>
<td>● Gasification product can be burned directly or used in gas engines. If cleaned significantly, it can be turned into syngas which is commonly used in methanol, ethanol, fertilizer, and electricity production.</td>
<td>● Uniformity of particulates is highly important to temperature propagation rates.</td>
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<td>● Pelletization, grinding, or blending, is necessary for some feedstocks prior to use in thermochemical conversion.</td>
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<td>● Feedstocks must be free of contaminants that can cause the thermochemical system to clog or render the operation ineffective by reducing peak temperatures.</td>
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<td>● Melted salts can combine with silica in dry gasification processes to form a sticky and highly mobile substance that blocks air flows and coats catalytic sites, affecting gas quality.</td>
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<td>Pyrolysis</td>
<td>● The main product of slow pyrolysis, biochar, is an appealing product for use in industrial and agricultural contexts because it readily adsorbs chemical compounds.</td>
<td>● Energy consumption is particularly significant if using wet feedstock.</td>
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<td></td>
<td>● Biochar shows promise as a means for carbon sequestration.</td>
<td>● Dewatering feedstocks before pyrolysis helps to reduce energy consumption.</td>
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<td>● Use of biochar in agriculture has many benefits, including improved biomass productivity, decreased irrigation costs, and drawdown of atmospheric carbon dioxide.</td>
<td>● The oxygen-rich bio-oil is unstable and acidic. Adding catalysts and hydrogen can remedy this problem.</td>
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<td></td>
<td>● Fast pyrolysis produces a bio-oil upon suitable upgrading that may be applied to engines or turbines or used as a refinery feedstock.</td>
<td>● Adding a catalyst adds costs and an additional need to understand maintenance, and replacement cycles.</td>
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<tr>
<td>Anaerobic digestion</td>
<td>● Can process biomass sources with high moisture contents (less than 40% dry matter), contrary to many other waste conversion methods.</td>
<td>● Controlled conditions and careful management for optimization of biogas production.</td>
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<td></td>
<td>● Generates biogas, which can be used to generate heat and power or upon separations and cleaning renewable natural gas.</td>
<td>● Biogas may require clean-up prior to use.</td>
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<td>● The nitrogen-rich slurry (digestate) can be used as a fertilizer.</td>
<td>● Biogas needs to be cleaned-up, concentrated, and compressed to make pipeline quality renewable natural gas.</td>
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<td>● Little energy demand for heating and electricity.</td>
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<td>● High energy-efficient process.</td>
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<td>● Little space requirements.</td>
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<td>● Low costs.</td>
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<td>● Odor reduction.</td>
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<td>● Air quality improvement.</td>
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<td>● Greenhouse gas emissions reduction.</td>
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<td>● Reduction in potential pathogens.</td>
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<td>Hydrothermal liquefaction</td>
<td>Composting</td>
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<td>• Can treat wet wastes without drying by maintaining a liquid water processing medium.</td>
<td>• Compost improves soil conditions.</td>
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<td>• Biocrude can be upgraded to the whole distillate range of drop-in fuel products.</td>
<td>• Replaces the use of chemical fertilizers.</td>
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<td>• High lipid concentrations are not required for effective HTL energy conversion</td>
<td>• Some aspects of the technology are still at R&amp;D level.</td>
<td>• It is best suited for “dry” manure (e.g., beef manure, poultry litter, horse bedding) due to optimal moisture content of the substrate being 75 percent to 85 percent.</td>
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<td>• The need for energy-intensive feedstock drying is potentially reduced or eliminated because a feedstock slurry is used as an input.</td>
<td>• No large-scale, reliable operation hydrothermal liquefaction plant exists in Washington State yet.</td>
<td>• The manure entering the system may need to have its nutrient ratio and moisture content adjusted prior to vermicomposting. Poultry manure in particular—due to its relatively high nitrogen-to-carbon ratio—generally requires added organic material, such as paper or cardboard, in a 4-to-1 ratio to achieve successful vermicomposting (Hamilton et al., 2008). The second disadvantage is the space needed for worm beds. Some have reported an application rate of 1.25 centimeters per day of fresh manure. A herd of 100 dairy cows would require 5,200 square feet, and a herd of 1,000 cows would require a plot the size of a football field. The facility would likely require a roof and temperature control.</td>
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<tr>
<td>• The high-efficiency chemistry of HTL transforms almost all of the biomass into biocrude oil, which largely self-separates from water as the reaction solution returns to standard conditions.</td>
<td>• Organic carbon is lost as carbon dioxide rather than being collected as methane.</td>
<td>• The manure entering the system may need to have its nutrient ratio and moisture content adjusted prior to vermicomposting. Poultry manure in particular—due to its relatively high nitrogen-to-carbon ratio—generally requires added organic material, such as paper or cardboard, in a 4-to-1 ratio to achieve successful vermicomposting (Hamilton et al., 2008). The second disadvantage is the space needed for worm beds. Some have reported an application rate of 1.25 centimeters per day of fresh manure. A herd of 100 dairy cows would require 5,200 square feet, and a herd of 1,000 cows would require a plot the size of a football field. The facility would likely require a roof and temperature control.</td>
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<td>• Further, HTL typically does not generate significant amounts of sludge or hazardous products of combustion such as NOx. However, this largely depends on the nitrogen content of the feedstock.</td>
<td>• Production of compost often causes odor and greenhouse gas emissions.</td>
<td>• The manure entering the system may need to have its nutrient ratio and moisture content adjusted prior to vermicomposting. Poultry manure in particular—due to its relatively high nitrogen-to-carbon ratio—generally requires added organic material, such as paper or cardboard, in a 4-to-1 ratio to achieve successful vermicomposting (Hamilton et al., 2008). The second disadvantage is the space needed for worm beds. Some have reported an application rate of 1.25 centimeters per day of fresh manure. A herd of 100 dairy cows would require 5,200 square feet, and a herd of 1,000 cows would require a plot the size of a football field. The facility would likely require a roof and temperature control.</td>
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<td>• Challenges associated with caring for the worms</td>
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5. Anaerobic Digestion

Anaerobic digestion (AD) is a process in which organic matter from wet organic wastes (i.e. liquid manure, food processing wastes, etc.) is converted into methane by bacteria in the absence of oxygen. The methane is then collected and may be used to generate combined heat and power (CHP) or treated to yield renewable methane fuel (RNG) [28]. In addition to biogas, a nitrogen-rich slurry (digestate) is also produced which may be used as a fertilizer [29].

Anaerobic digestion consists broadly of four phases, namely, enzymatic hydrolysis, acidogenesis, acetogenesis, and methanogenesis [30]:

• **Enzymatic hydrolysis:** through enzymatic hydrolysis the polymers are broken down into oligomer or monomeric units. For example, polysaccharides are broken down into oligosaccharides and monosaccharides, proteins are broken down into peptides and amino acids, and lipids are converted into glycerol and fatty acid.

• **Acidogenesis:** in the acidogenesis phase the products of enzymatic hydrolysis are fermented to volatile fatty acids (VFA) such as acetate, propionate, butyrate, valerate, and isobutyrate along with carbon dioxide, hydrogen, and ammonia.

• **Acetogenesis:** in this phase acetogenic bacteria (e.g., Syntrophomonas and Syntrophobacter) convert the acidogenesis products into acetates and hydrogen.

• **Methanogenesis:** in this last phase, methane is produced either by fermentation of acetic methanogenesis carried out by methanogenic bacteria or by reduction of carbon dioxide.

For anaerobic digestion to work with high metabolic activity, it is imperative to have controlled environmental conditions, as the methanogenic bacteria are very sensitive to unfavorable survival conditions.

5.1 Process Parameters

Several factors influence biogas production, namely particle size and mixing, alkalinity and pH, temperature, organic loading rate, hydraulic retention time, chemical oxygen demand (COD) as well as the variety of feedstock used [31]. These factors are briefly discussed below:

• **Particle size and mixing:** The particle size of the substrate has a substantial effect on methane production. By reducing the particle size of the substrate, the surface area is increased allowing for greater exposure of the substrate to microbial activities. This results in higher solubilization of the food waste and VFA production, with improved biogas production. However, when the particle size is excessively reduced (0.393mm or smaller), VFA accumulation occurs leading to a deterioration in methane production. In addition to particle size, mixing is highly advantageous in anaerobic digestion as it leads to a more even dispersion of nutrients, bacteria, and substrate as well as temperature.

• **Alkalinity and pH:** One of the most influential parameters on the process of anaerobic digestion is pH as it can affect the equilibrium between most chemical species. The anaerobic digester contains a consortium of bacteria with different optimal pH ranges. Specifically, the ideal pH range for acid-producing bacteria is 5.0-8.5, whereas methanogens prefer a pH range of 6.5-8.0. Optimally, anaerobic digesters are run within a pH range of 7.0-8.5. Methane production is reported to cease once the pH drops below 6.0.

• **Temperature:** Similarly to pH, different bacteria have different optimal temperatures for their growth. Commonly anaerobic digesters either function within a mesophillic temperature range (at approximately 35°C) or within a thermophillic temperature range (between 50°C-57°C).
• Organic loading rate and hydraulic retention time: Organic loading rate (ORL) can be defined as the quantity of substrate added per digester volume and time. For solid wastes OLRs are typically measured based on volatile solids (VS) added per unit of time, however, for liquid wastes chemical oxygen demand (COD) per unit of time is generally used. The amount of time that the sludge or wastewater remains in the reactor is known as the hydraulic retention time (HRT). Anaerobic digesters usually have an HRT of 10-25 days or more. Materials with high cellulose content are degraded at a slower rate than materials with high fermentable sugars content which are quickly degraded. With higher organic loading rates, a higher HRT is usually required.

• Chemical Oxygen Demand (COD): COD is typically used as an indication of the concentration of pollutants in a sample of substrate. It can be defined as the total oxygen necessary to oxidize all organic material into carbon dioxide and water and the inorganic chemicals such as ammonia and nitrate.

• Substrates: The variety of substrate used directly influences both the biogas yield and quality. For example, organic matter rich in fats/lipids have a higher biomethane potential than those rich in carbohydrates or proteins due to the extensive oxidation required to break down fats compared to carbohydrates or proteins. The carbon to nitrogen ratio (C/N) is an important factor in biogas production. Ratios between 25-30 are considered optimal for anaerobic digestion. Lower C/N ratios may lead to accumulation of volatile fatty acids with consequent pH drop leading to unfavorable conditions for methanogens and digester failure. Equally undesirable are high C:N ratios which may produce lower methane yields due to a lack of nitrogen for cell growth.

5.2 Biogas yield from different feedstock
Several studies have investigated substrate mixtures which give the highest biogas and methane yields in anaerobic digestion [31], [32]. In this section we discuss how biogas and methane yields vary based on the feedstock composition for single substrates and mixed substrates.

5.3 Single Substrates

• Fruit waste: Fruit waste as a single substrate has limited potential for biogas production. The high sugar content can lead to a rapid decrease in pH ultimately leading to digester failure [33]. Additionally, fruit waste alone does not provide all the necessary vitamins and micro-nutrients (e.g., phosphorous and nitrogen) necessary to sustain the growth of bacteria involved in methane production. One option for improving biogas yields from fruit waste is through the addition of co-substrates.

• Livestock manure
  • Cattle manure: Biogas plants which use dairy manure as a sole substrate are known to produce low biogas yields per unit mass of manure added and are associated with a low return of investment. Cattle manure is considered uneconomical as a sole substrate for anaerobic digestion. However, it is a favorable co-substrate for anaerobic digestion as it contains almost all essential nutrients as well as trace elements important for microbial growth. Good candidates for co-digestion with cattle manure are substrates rich in lipids and/or carbohydrates that have a high VS content.

• Swine and poultry manure: Unlike cattle manure, both poultry and swine manure frequently produce high total ammonia concentrations, which have an inhibitory effect to the anaerobic digestion process. Ammonia inhibition is therefore more likely to occur when swine or poultry manure are used as co-substrates rather than when cattle manure is used.

• Lignocellulosic biomass: Lignocellulosic biomass generally refers to the fibrous, wood-like and usually inedible fraction of plant matter [34]. Lignocellulose typically resists degradation
and provides hydrolytic stability and structural robustness to the cell walls of plants through the crosslinking of cellulose and hemicellulose to lignin by means of ester and ether bonds. As a result of the recalcitrance to degradation, crops with high lignocellulose contents usually require pretreatments prior to anaerobic digestion to free cellulose from lignin, thus making it available for degradation. Unit operations such as mechanical milling, washing with hot water, steam explosion, ammonia fiber expansion and alkali- or acid pretreatments are often used for this purpose.

5.4 Multi-substrate Studies

Many studies involving more than two substrates show that co-digestion improves digester stability and biogas production. In general, having a wide variety of substrates and high lipid and nitrogen content is important to improve methane yields.

- **Food waste and manure**: The combination of food waste with manure is likely to provide good methane yields; however, this is largely dependent on the composition of food waste and the ratios of substrate used. The analysis of the literature shows that the highest methane yields are achieved when using feedstocks with a substrate composition of 50% manure or greater.

- **Lignocellulosic biomass**: Lignocellulosic biomass can be used as a co-substrate for anaerobic digestion as it is a rich source of carbon. However, pretreatment of lignocellulosic biomass prior to anaerobic digestion is recommended.

Kell (2019) conducted a mixed interaction study to identify the substrate mixtures which gave the highest biogas and methane yields based on season availability and with the highest waste disposal value (i.e., with the least manure and largest quantity of waste products) [31]. Results showed that all the selected fruit waste feedstocks produced a methane concentration above 40% when supplemented with 50% manure. To decrease reliance on manure as the main nitrogen supplier, food waste was initially selected as an additional feedstock to the fruit waste to provide an additional source of nitrogen. A second mixture design incorporating a slower degrading substrate (i.e., lignocellulosic biomass) as an additional feedstock to the fruit waste was conducted. It was found that the lignocellulosic biomass supplementation produced much higher biogas and methane yields when co-digested with fruit wastes than the initial mixture design with food waste. A substrate combination of 20-30% fruit waste, 50-40% manure and 30% lignocellulosic biomass produced the highest biogas and methane yields.

Several other studies highlight the benefits of co-digestion. Pöschl et al. (2010) emphasize how most biogas systems in Germany co-digest between three and five feedstocks [35]. The authors explain how single feedstock digestion is unsustainable for large-scale plants and how rapid acidification of easily degradable feedstock, e.g., food residues, may rapidly result in inhibition of the AD process [32],[36]. Lisboa and Lansing (2013) co-digested four food waste substrates (meatball, chicken, cranberry, and ice cream processing wastes) for 69 days with flushed dairy manure and reported an increase in methane production. Their findings suggested that addition of even a small quantity of food waste to dairy manure significantly enhanced the methane levels [30].

5.5 Pretreatment Technologies

Lignocellulosic biomass typically resist degradation due to lignin recalcitrance. In case of waste with high lignocellulosic content, AD can be associated with lowered carbon conversion efficiency and a biomass pretreatment is recommended prior to entering the digester. Advanced Wet Oxidation & Steam Explosion pretreatment (AWOEx) is a thermochemical process integrating wet oxidation and steam explosion [37]. In this process, biomass is exposed to an oxidizing agent such as air, hydrogen peroxide, pure oxygen etc. under high temperatures (over 140 °C) and pressures (over 10 bars) for the duration of 15 to 45 min.
Dutta et al. (2022) evaluated the effect of the AWOEx pretreatment on the methane yield at variable temperatures (165–200 °C), residence time (15–45 min) and oxygen dosage (1%–10% based on VS concentration) [38],[39]. The results show that the highest average methane yields of 183 mL/g VS and 170 mL/g VS were found for the bioreactors receiving pretreated biomass at 165 °C with a retention time of 15 min and 10 % O$_2$ (Condition 1), and 182.5 °C with a retention time of 15 min and 5.5 % O$_2$ (Condition 2). This corresponds to an increase in the methane production of 156.2 % and 140.5 % compared to the methane production from AD without pretreatment.

AWOEx was originally developed for pretreating lignocellulosic biomass materials for producing biofuels. AWOEx has been tested with 26 different types of biomass and has shown a superior ability to produce a pretreated homogenized material at 30% DW, which can produce high sugar yield (150 g/L) with low cellulolytic enzyme doses. This novel pretreatment technology has the potential to significantly reduce cost and energy consumption as well as greenhouse gas emission of treating wet waste though AD [40] and allow to expand RNG production to a broader range of biomass feedstock.

5.6 Biogas from Anaerobic Digestion

Biogas predominantly consists of methane (50-70%) and carbon dioxide (30-40%), however it can also contain other elements that are present in small amounts but can affect the properties of the biogas, including nitrogen (0–3%), water vapor (5–10%), oxygen (0–1%), hydrogen sulfide (0–10,000 ppm), ammonia (0–200 mg/m$^3$) and siloxanes (0–40 mg/m$^3$). Generally, the percentage of methane and carbon dioxide fractions vary with the type of feed material as well as the operating conditions of the bioreactor [41]. Table 2 shows common sources of biogas and the different gases or contaminants that can be found. Such variations can complicate the possible end uses for biogas.

<table>
<thead>
<tr>
<th>Sources</th>
<th>Biogas characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landfills</td>
<td>CH$_4$, CO$_2$, H$_2$S, water vapor, other sulfides and mercaptans, siloxanes, non-methane organic compounds, oxygen, nitrogen, ammonia, and other trace gases</td>
</tr>
<tr>
<td>Wastewater treatment plants</td>
<td>CH$_4$, CO$_2$, H$_2$S, water vapor, siloxanes, and possibly traces of nitrogen and ammonia compounds</td>
</tr>
<tr>
<td>Dairy manure</td>
<td>CH$_4$, CO$_2$, H$_2$S, and water vapor</td>
</tr>
<tr>
<td>Food processing byproducts</td>
<td>CH$_4$, CO$_2$, H$_2$S, and water vapor</td>
</tr>
<tr>
<td>Municipal organic waste</td>
<td>CH$_4$, CO$_2$, H$_2$S, water vapor, siloxanes, other gases in trace amounts</td>
</tr>
</tbody>
</table>

- **Hydrogen sulfide (H$_2$S):** Of the inorganic acids produced in the digester, hydrogen sulfide is the most detrimental [31] as it can corrode the metal components of the boilers, internal combustion engines, and gas pipelines [43]. Excess hydrogen sulfide is usually the result of the digestion of large amounts of sulfur-containing waste such as proteinaceous compounds. Hydrogen sulfide can be scrubbed from the biogas; however the process is expensive and likely cost-prohibitive for small treatment plants.

- **Ammonia (NH$_3$) and halogenated hydrocarbons:** The presence of ammonia and halogenated hydrocarbons in biogas affects its ignition properties and can cause corrosion in combined heat and power (CHP) engines and gas pipelines after combustion.

- **Carbon dioxide (CO$_2$):** Carbon dioxide should be removed from biogas before adding the methane to the natural gas grid because high concentrations of CO$_2$ reduce its heating value. Carbon dioxide, hydrogen sulfide, and water vapor are the primary contaminants of biogas of importance for its use in vehicle engines, CHP engines, boilers, and natural gas grid, and they should all be removed before utilizing the biogas as an alternative to natural gas.

Biogas can be used to produce many forms of energy [3]. With minimal conditioning (i.e., removing water and hydrogen sulfide), raw biogas has the characteristics of a medium-BTU gas, providing about 500-600 BTU per cubic foot. This biogas can be burned directly in heaters, stoves, or boilers to provide thermal energy, or converted by various types of generators, turbines, or fuel cells into renewable heat and electricity (combined heat and power, or CHP).
The biogas industry in Washington has been through many stages of development. Some landfills and wastewater treatment plants have used biogas productively on site for decades, while others simply flare the biogas. In the past, Washington’s dairy industry was the primary target for digester developers, but new development in this sector has slowed.

Washington ranks 22nd out of 50 states for its biogas production potential. The American Biogas Council estimated that up to 18.54 billion cubic feet of renewable methane from biogas could be produced each year for energy, fuel, heat, and more [44].

5.7 Upgrading technologies for the production of renewable natural gas from biogas

Several biomass upgrading technologies have been developed to remove contaminants from biogas and upgrade it to Renewable Natural Gas (RNG) [41]. They can be divided in physicochemical methods and biological methods (Figure C-1.1). Physical adsorption, chemical adsorption, pressure swing adsorption, and membrane separation are considered conventional biogas upgrading methods, while biological-based, cryogenic, and hybrid technologies are considered as emerging technologies. Conventional biogas upgrading methods are commonly used and account for 99% of all upgrading plants:

- **Physical adsorption by water scrubbing** is the most used technology for the removal of H₂S and CO₂ from the biogas. About 41% of the biogas upgrading plants in the world employ water scrubbing technology [45]. The water scrubbing process is based on the higher solubility of H₂S and CO₂ in water as compared to CH₄. For instance, CO₂ has 26 times higher solubility in water as compared to methane at 25°C. The physical water scrubbing is carried out at a pressure of 6–10 bars. Nevertheless, this process consumes large amounts of water.

- **Chemical adsorption with amine** is another commonly used conventional technology for the upgrading of raw biogas, but a high amount of energy is required for regeneration of the chemicals used [46], which can increase the operational costs of the process.

- **Membrane technologies** are also used for biogas upgrading. However, they are expensive. These disadvantages may be mitigated by combining two or more technologies together to develop hybrid technologies.

- **Cryogenic separation** occurs at a temperature of -170°C and a pressure of 80 bars. Different components in biogas are separated based on their different liquefaction temperatures and pressures. The main challenges associated with cryogenic separation of biogas are the higher operating and investment cost, the clogging of the pipelines due to the higher concentrations of impurities and the CO₂ and CH₄ losses.

- **In-situ biological biogas upgrading** within the biogas reactor is also a promising biomethane production technique with over 85% methane recovery, but the major challenge with this process is the inhibition of methanogens due to the increase of pH above 8.5. This obstacle may be overcome by the co-digestion of the substrate with an acidic feedstock or the external control of pH during the upgrading process.

- **Photoautotrophic process** has a methane recovery of about 97%. The main challenges associated with the photoautotrophic process are the high energy demand and investment costs. Moreover, during the upgrading of biogas by microalgalphoto bioreactors, the fixation of 1 mol of CO₂ produces 1 mol of oxygen, which affects the quality of the final product.
Figure C-1.1: Upgrading technologies for the production of Renewable Natural Gas from biogas.
6. Renewable natural gas from anaerobic digestion

Biogas upgrade results in a high-BTU gas called Renewable Natural Gas (RNG) or biomethane. The desired end use for RNG guides the extent of scrubbing or upgrading required of the raw biogas. RNG can be used in the same appliances, equipment, engines, and vehicles that use natural gas. RNG applications include [3]:

- **Injection into the natural gas distribution system.** To be transported in a pipeline, RNG needs to meet prescribed quality standards, which include having an energy value of 985 BTU per cubic foot or greater. Residents and businesses in Washington State consume 308 trillion BTU of natural gas annually, which is equivalent to 308 billion cubic feet [11]. Natural gas is mainly used for residential and commercial cooking and heating, industrial energy, and electricity generation. About 34% of natural gas in Washington is used in the residential sector, 30% in the industrial sector, 22% in the commercial sector, and 14% for power generation [47]. Washington has no in-state production of natural gas and currently relies on supplies from Canada and the Rocky Mountain states. This makes the state’s utilities vulnerable to fluctuations in supply and price.

- **Use to fuel natural gas vehicles.** For direct use in vehicles, RNG needs to be scrubbed of hydrogen sulfide, siloxanes, and other trace gases, but engines can tolerate some nitrogen and as much as 10% carbon dioxide so the required upgrade may only be to 900 BTU per cubic foot. Because the fueling infrastructure is RNG-compatible, vehicles that use natural gas can easily use RNG. However, very little natural gas is currently used for transportation in Washington State. Among the more advantageous uses of RNG is the displacement of gasoline and diesel fuels in vehicles. Given the increasing emphasis on electrifying transportation, the best opportunity to use RNG in transportation is through fuel substitution in local fleets, heavy-duty over-the-road vehicles, and marine and rail vehicles [48].

### Table C-1.3: Existing RNG production facilities in Washington State

<table>
<thead>
<tr>
<th>Facility</th>
<th>Type</th>
<th>RNG [MMBtu/yr]</th>
<th>Natural gas market [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cedar Hills Landfill (King County)</td>
<td>Landfill</td>
<td>1,500,000</td>
<td>0.5%</td>
</tr>
<tr>
<td>Bioenergy WA/Puget Sound Energy</td>
<td>Landfill</td>
<td>2,100,000</td>
<td>0.7%</td>
</tr>
<tr>
<td>Roosevelt Landfill (Republic Services)</td>
<td>Landfill</td>
<td>2,300,000</td>
<td>0.7%</td>
</tr>
<tr>
<td>Kittitas County PUD</td>
<td>Landfill</td>
<td>300,000</td>
<td>0.1%</td>
</tr>
<tr>
<td>South Treatment Plant (King County)</td>
<td>Wastewater treatment</td>
<td>300,000</td>
<td>0.1%</td>
</tr>
<tr>
<td>Puget Sound Energy</td>
<td></td>
<td>4,003,340</td>
<td>1.3%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>4,003,340</strong></td>
<td><strong>1.3%</strong></td>
</tr>
</tbody>
</table>

6.1 RNG projects in Washington State

Currently in Washington State several anaerobic digesters are already operating on landfills, wastewater treatment plants, and dairies. One landfill, two wastewater treatment plants and eight dairies are currently using their biogas to produce renewable electricity. The two largest landfills in the state and a major metropolitan wastewater treatment facility are already upgrading their biogas to RNG and injecting it into the natural gas pipeline grid [49].

As shown in Table 3, the current annual supply of RNG to the pipeline in Washington State is estimated to be 4 million MMBtu. According to the U.S. Energy Information Administration, the volume of natural gas delivered annually to end users in Washington State averaged 300 million MMBtu between 2013 and 2017. Therefore, overall, RNG from these three facilities is equivalent to 1.3 percent of current natural gas consumption [5].

At present, this RNG is being sold into the California market due to the significant value available under that state’s low-carbon fuel standard.

6.2 Agricultural symbiosis projects for RNG production

In this section we present a case study of a potential agricultural symbiosis project in Washington State. The project is about the potential RNG production from anaerobic co-digestion of different agricultural waste streams. Based on the results in Kell (2019) [31], we selected an anaerobic digestion substrate characterized by 20% pomace, 30% wheat straw and 50% manure.
First, we analyzed existing data of wet waste availability, including manure, wheat straw and apple & pear pomace, to identify potential clusters where resources are available within a certain distance from where the AD plant would be located (13 miles for manure, 50 miles for wheat straw, apple and pear pomace). We identified four main sites where AD plants could potentially be located. These are represented with the numbers 1-4 in Figure C-1.2 and include Lynden, Sunnyside, Warden, and Burbank. The availability of manure, wheat straw, and pomace within the selected distances (13 miles for manure, 50 miles for wheat straw, apple and pear pomace) are shown in Table 4 for each of the selected site.

Community digesters represent a potential solution for small and medium-sized farming operations to overcome some of the economic obstacles associated with digesting waste [11]. It has been estimated that the maximum distance that dairy manure can travel is 13 miles before it requires more energy to move than can be recovered from the system [31].

The bottleneck feedstock in the selected sites was pomace, so we selected Sunnyside as the potential site of the agricultural symbiosis project. The amount of manure and wheat straw needed to obtain a substrate composition of 20% pomace, 30% wheat straw and 50% manure given the availability of pomace is reported in Table 5.

Based on Kell (2019), the biogas and methane yields for the selected AD substrate composition are 410.01 mL/gVS and 167.1 mL/gVS respectively. Accordingly, we calculated an overall biogas and methane potential of 3.84 and 1.56 billion cuft/yr respectively (Table 6). Assuming to recover 95% of the methane in the biogas stream via upgrading and an energy value of 985 BTU per cubic foot of RNG, we estimated an RNG potential of approximately 1,500,000 MMBtu/yr. This result is of the same order of magnitude of the RNG production at the Cedar Hills Landfill (King County) Bioenergy WA/Puget Sound Energy facility (Table 3).

### Table C-1.5: Availability of cattle manure, wheat straw and pomace in Sunnyside, WA, considering a substrate composition of 20% pomace, 30% wheat straw, and 50% manure.

<table>
<thead>
<tr>
<th>Nearby City</th>
<th>Label Number</th>
<th>Manure (13 miles) [dry tons/yr]</th>
<th>Wheat straw (50 miles) [dry tons/yr]</th>
<th>Apple &amp; Pear Pomace (50 miles) [dry tons/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunnyside</td>
<td>2</td>
<td>160,048</td>
<td>83,468</td>
<td>58,407</td>
</tr>
</tbody>
</table>

### Table C-1.6: Potential biogas and RNG production from a hypothetical AD plant located in Sunnyside, WA using a substrate made of 20% pomace, 30% wheat straw, and 50% manure.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunnyside</td>
<td>2</td>
<td>3.84</td>
<td>1.56</td>
<td>~1,500,000</td>
</tr>
</tbody>
</table>

### 6.3 RNG production potential in Washington State

According to the American Biogas Council, Washington State ranks 22nd out of 50 states for its biogas production potential. While Washington State currently has 49 biogas projects, there is the potential to build 231 new biogas systems, distributed as shown in Figure C-1.3.
The American Biogas Council estimates that up to 28.96 billion cuft per year of biogas could be produced in Washington State [44]. The biogas could be upgraded to 18.54 billion cuft/yr of RNG corresponding to 16,700,000 MMBtu/yr (assuming an energy value of 900 BTU per cubic foot of RNG [3]). Of the total biogas produced, about 52 percent would be produced from manure, 45 percent from food waste, and 3 percent from wastewater treatment plants.

### 6.4 Economic impacts of RNG

The job creation potential from RNG development is significant. The American Biogas Council estimated that constructing 231 new biogas systems in Washington State would generate about $694 million in capital investments, 5,786 construction jobs and 384 permanent jobs.

At present, producing RNG, especially in small volumes at distributed locations, is more expensive than extracting fossil natural gas from underground reserves. Many factors affect the costs of building RNG facilities including the type and size of project, biogas characteristics, distance to the pipeline, type and pressure of the required interconnection, and others. The combined capital investment for the three existing RNG projects in Washington has been reported by facility operators to be between $80 and $100 million. Landfills, with their sizable RNG resources, often require the greatest capital investment. However, they offer excellent economies of scale.

RNG production costs vary between less than $1 per MMBtu for some large landfills to $12 per MMBtu for small dairies. Large wastewater treatment facilities might produce RNG for as low as $5 per MMBtu while small wastewater treatment plants and large dairies could have production costs around $9 per MMBtu. An additional $3 per MMBtu should be considered to account for the cost of accessing and injecting RNG to the pipeline. Previous work found that even though the direct cost to produce, clean and deliver RNG into a natural gas pipeline often falls in the range of $10 to $20 per MMBtu, the total project value required to attract private investment can be $20 to $30 per MMBtu [49]. Community digesters represent a potential solution for small and medium-sized farming operations to overcome some of the economic obstacles associated with digesting waste [11],[32].

### 6.5 Market drivers and incentive schemes

The U.S. Renewable Fuel Standard and California’s Low Carbon Fuel Standard are currently the key market drivers for RNG development. The U.S. Renewable Fuel Standard, which originated with the Energy Policy Act of 2005, requires renewable fuels to be blended into transportation fuels [53]. Under the Renewable Fuel Standard program, obligated parties (refiners and importers of gasoline or diesel) achieve compliance by blending renewable fuels into transportation fuel or by obtaining credits (called Renewable Identification Numbers, or RINs).
The Low Carbon Fuel Standard (LCFS) was implemented by the California Air Resources Board (CARB) in 2011, as one of the nine early action measures to reduce California's greenhouse gas emissions [54]. The LCFS policy initiatives have helped kickstart the market for RNG and renewable electricity generated from on-farm anaerobic digesters.

6.6 Environmental impacts of RNG

The global warming impact of fuels is commonly assessed in terms of carbon intensity (CI). Carbon intensity (CI) is calculated based on a lifecycle analysis (LCA) of the production, distribution, and use of each fuel, from well to wheels (for petroleum or natural gas) and from field, farm or landfill to wheels (for biofuels such as ethanol, biodiesel and RNG). CI values are expressed in terms of grams of carbon dioxide equivalent gases per megajoule of energy (gCO$_2$e/MJ). California and Oregon use CI calculations for transportation fuels to manage their Low Carbon Fuel Standard programs [3].

Production and use of RNG provide multiple GHG emission reduction benefits. For example, RNG from a dairy farm digester produces biogas from manure previously stored in lagoons where it released methane into the air. The global warming potential of methane is 27-30 times greater than CO$_2$ when measured on a 100-year scale. On a shorter 20-year scale, methane has 81 to 83 times the global warming potential of CO$_2$. Capturing methane, while producing and using RNG, provides major global warming reduction benefits.

According to the California Air Resource Board, the certified CI for these fuels generated from manure feedstock ranged from -151 to -532 with an average of -317 [11]. These certified CIs are relative to the diesel CI of 100 [55]. CIs play a vital role in the administration of low-carbon fuel standards (LCFS) in states like California and Oregon.

Diesel fuel is a major source of air pollution, smog forming gases, and fine particulate matter. It has been estimated that thousands of people die prematurely each year from excessive exposure to diesel particulate pollution. The Lung Association of Washington has identified similar health concerns, especially from diesel pollution along major freight corridors. When RNG is used as a transportation fuel, the reported reduction in the environmental impacts are significant:

- Carbon dioxide (CO$_2$) reduced by 10% to 30%
- Carbon monoxide (CO) reduced by 70-90%
- Nitrogen oxide (NOx) reduced by 75-95%
- Particle matter (PM) reduced by up to 90%
- Sulfur oxide (SOx) reduced by up to 99%
- Volatile organic compound (VOCs) reduced by 89% [3].

At present, nearly all Washington dairy-based anaerobic digesters are generating electricity from their biogas for sale to Puget Sound Energy. However, an industry study [56] suggests natural gas offers greenhouse gas reduction advantages over heating with electricity, so many gas industry experts are encouraging using RNG for heating, not just transportation.

7. Key findings

- Among existing, well-established technologies applicable to agricultural waste streams, anaerobic digestion (AD) offers great opportunities for agricultural symbiosis projects in Washington State. Through AD, wet organic wastes can be converted to biogas which may be used to produce renewable natural gas (RNG) or combined heat and power (CHP).
- The composition of the feedstock used in AD directly influences the biogas yield and quality, and combinations of different wastes may be most productive. Carbon/Nitrogen (C/N) ratios between 25-30 are considered optimal for digester functioning. Fruit waste as a single substrate can lead to a rapid decrease in pH due to the high sugar content, thus inhibiting biogas and methane production.
Agricultural symbiosis projects utilizing mixed waste streams have the greatest potential to maximize biogas production through agriculture. Adding manure as a source of nitrogen to the fruit waste substrate considerably increases biogas and methane yields. Alongside manure, supplementing lignocellulosic biomass (such as crop residues) to the fruit waste-manure substrate results in much higher biogas and methane yields.

Transportation is a key consideration for wet wastes, because it is heavy due to the high moisture content. Solutions to optimize logistics include analysis to find areas where wastes are produced in proximity across sectors, co-location of waste-generating entities, piping when wastes will be generated over the long-term at short distances from each other, and - when trucking is needed - utilizing clean fuels for transportation to reduce the carbon footprint.

An analysis of existing RNG facilities suggests that AD is underutilized in Washington. The RNG production potential is vastly underutilized in the United States, with existing facilities representing less than 20% of the total potential nationwide. Washington State ranks 22nd of 50 states.

Agricultural symbiosis projects that use AD technology have the potential to generate capital investments, permanent jobs, and additional revenue within the agricultural sector in Washington while benefiting the climate. The energy generated by a digester comes from biomass and therefore climate benefits are generated by displacing fossil fuels from fossil-based natural gas, heat, and electricity. In some cases, climate benefits also result from reducing methane emissions from current waste management practices.

Among emerging technologies, hydrothermal liquefaction (HTL) presents great opportunities for agricultural symbiosis applications in Washington State. HTL converts agricultural wet waste streams into biocrude and biofuels and can be used to treat a diverse range of waste streams, including food waste, sludge, manure, oil, fats and grease and others.

Other technologies for wet wastes, e.g., composting, biochar and compost blending, vermicomposting, larvae-based composting, and vermifiltration and others, may be suitable for smaller scale opportunities.
References


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