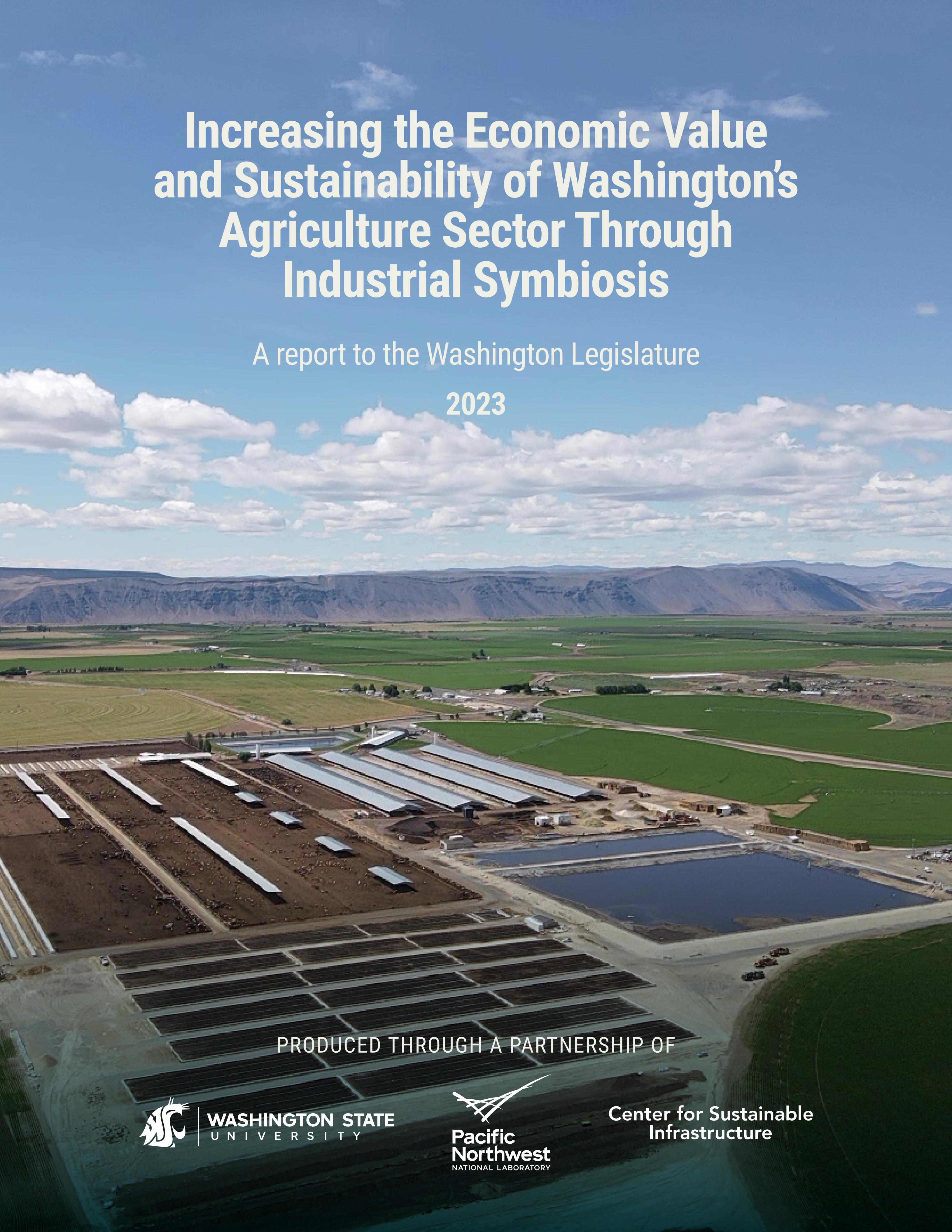

Increasing the Economic Value and Sustainability of Washington's Agriculture Sector Through Industrial Symbiosis

A report to the Washington Legislature

2023

PRODUCED THROUGH A PARTNERSHIP OF

WASHINGTON STATE
UNIVERSITY

Pacific
Northwest
NATIONAL LABORATORY

Center for Sustainable
Infrastructure

Please Note: This report offers technology and resource assessments to enable Washington policy makers to make more informed decisions “for increasing the economic value and sustainability of Washington’s agriculture sector through the use of industrial symbiosis principles,” as directed by the 2022 Washington State Legislature.

Washington State University enlisted expert investigators with Pacific Northwest National Laboratory and the Center for Sustainable Infrastructure as partners to develop this report. In addition to the five lines of targeted research that will be highlighted in the Key Findings section of this report and detailed in Appendices I - IV, technology and resources findings that enable policy recommendations were informed by interviews and consultations with several dozen agriculture symbiosis experts, innovators, and stakeholders, led by CSI.

The recommendations were developed by CSI to synthesize insights from the project’s key findings and consultations, and to distill a set of strategic recommendations to achieve the Legislature’s intent, as expressed in the budget proviso directing this study.

CSI solicited review and feedback on a draft of these recommendations from project partners and the experts, innovators and stakeholders consulted by the project. The final recommendations contained in this report, however, are the responsibility of CSI, and do not necessarily reflect the position of partner organizations or any of the leaders and organizations consulted.

Cover photo credit: Perca, Inc.

I. Introduction & Overview

The 2022 Washington State Legislature directed Washington State University (WSU) to partner with organizations with relevant expertise to “develop recommendations for increasing the economic value and sustainability of Washington’s agriculture sector through the use of industrial symbiosis principles.”

In response, this Agriculture Symbiosis report has been produced by WSU in partnership with the Center for Sustainable Infrastructure (CSI) and the Pacific Northwest National Laboratory (PNNL) through research and consultations with stakeholders and experts.

Agriculture Symbiosis happens when food, beverage, or farm businesses partner with each other, or with businesses from other industry sectors, to share their surplus resources – energy, water, and organic ‘wastes’ – for mutual economic benefit. Successful symbiosis projects offer both a compelling business case for each participating company and deliver substantial sustainability performance improvements. For the purposes of this report, the terms “agriculture sector” and “agriculture symbiosis” include the food and beverage sectors to reflect a more holistic food system perspective that includes broader agriculture supply chains.[1]

This age-old strategy of generating economic value by sharing and re-using resources such as water, heat, and organic materials is being taken to promising new levels, contributing to business growth, improving energy and water efficiency, building soil health, addressing emissions, and helping maintain the state’s clean water and air.

Agriculture is among Washington’s most successful and important industry sectors, generating over $10.2 billion in production value in 2022, according to USDA and National Academy of Sciences figures. Competition and consumer demands within the farming, food, and beverage sectors means that businesses can benefit from new efficient processes that produce higher value while reducing wastes and costs.

Washington agriculture has achieved remarkable levels of productivity and competitiveness through a history of innovation. And through a rich history of agricultural cooperatives, deep experience in economic cooperation is woven throughout our food systems. As on-farm, in-house and collaborative innovations continue, new value and new products will continue to sustain and grow Washington’s agricultural economy.

Building on this history, this report explores whether there are new, untapped opportunities to enhance agriculture symbiosis by finding new value from waste, or ‘surplus resources,’ with agreements and infrastructure that connects multiple parties. With these opportunities in mind, we seek to identify what kinds of support and solutions are needed to overcome existing barriers and help individual businesses come together in symbiotic relationships that benefit all parties involved and Washington’s citizens.

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[1] While we recognize the potential for symbiosis efforts that involve post-consumer food waste, this report focuses on organic waste streams from farm to processor to retailer, but prior to purchase by consumers.

There are many potential benefits of agriculture symbiosis for Washington's agricultural economy and communities. Symbiosis projects can convert waste into new products and revenues. Waste-to-resource products can include renewable energy and fuels, clean fertilizers and soil amendments, recycled water, and feedstocks for a range of bio-based products, such as higher value proteins and polymers. Recycled heat, water, and organic materials can replace a portion of imported, price-volatile feedstocks and resource inputs for agriculture producers. By providing additional strategies for maintaining air and water quality, symbiosis can also reduce waste management and compliance costs and liabilities.

By supporting the development of high-quality agriculture symbiosis projects, Washington will be better positioned to secure funding from an unprecedented wave of anticipated federal investment over the coming decade, as projects with demonstrated economic, environmental, and social benefits gain competitive advantage. Further, Washington companies that develop know-how in agriculture symbiosis and resource efficiencies can leverage their leadership and track record of successful projects to market their services in other areas of the U.S. and globe.

This report is organized as follows:

Throughout the report, some of Washington's agriculture symbiosis pioneers are profiled. These innovators are certainly not the only symbiosis innovators in Washington. However, together they offer a reasonable illustration of the diversity and range of forward-thinking agriculture symbiosis projects around the state today.

II. Project Genesis

Beginning in 2017, over two dozen Washington state legislators – evenly distributed between Republicans and Democrats -- participated in study tours in Denmark[2] where they observed industrial symbiosis (IS) in action.

These bipartisan legislators found significant common ground in seeing the potential to adapt Denmark's IS model to benefit industries in a wide range of Washington communities, from very small towns to bigger cities, and at the same time gain substantial economic, environmental, and social benefits for Washingtonians.

Legislators were especially inspired by Kalundborg, Denmark – home of the world's oldest and most advanced industrial symbiosis, where over two dozen resource-sharing agreements are delivering very substantial economic and climate returns (see Appendix D).

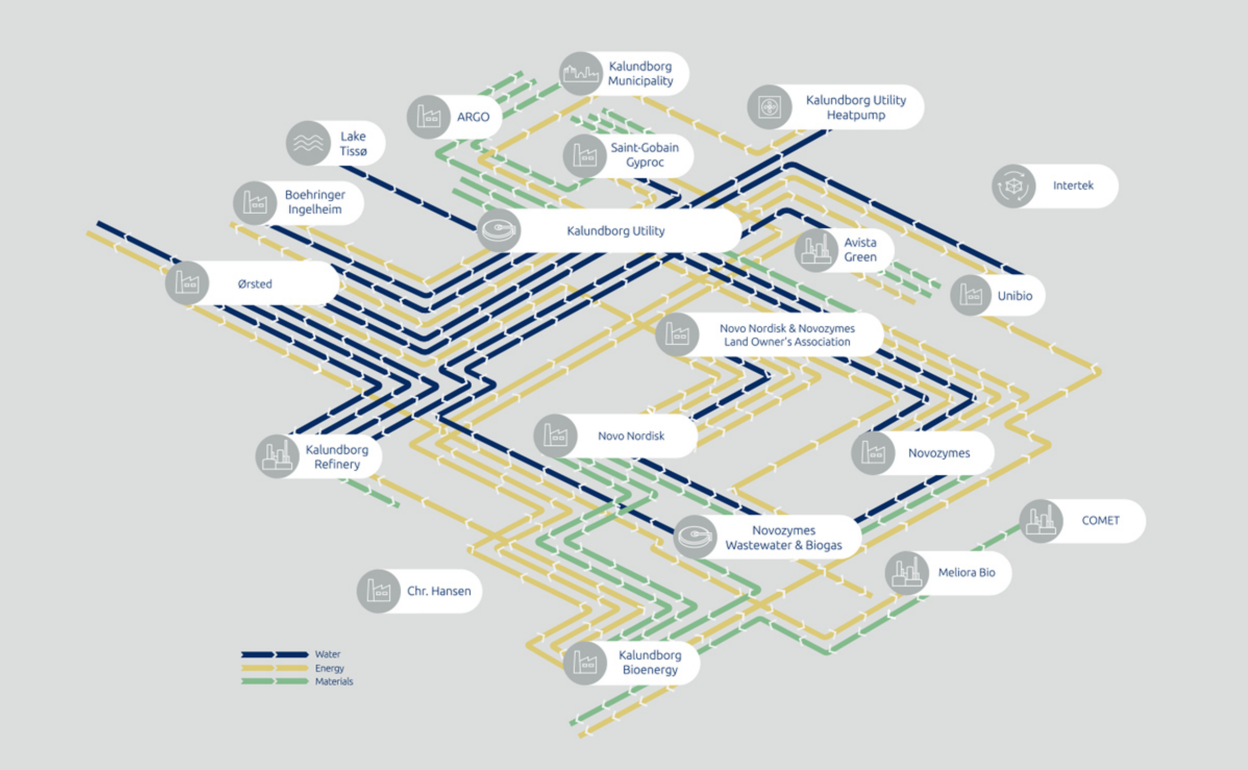

Image Credit: Kalundborg Symbiosis

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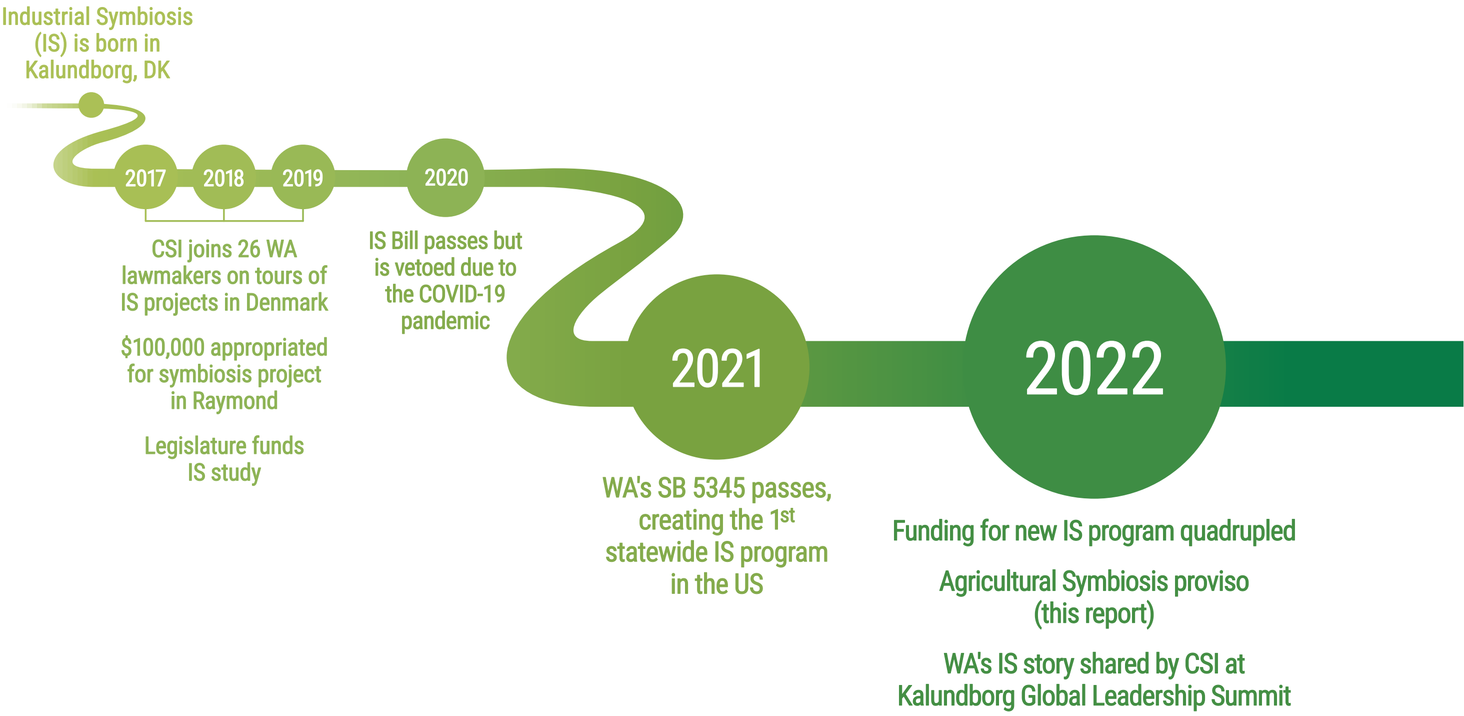
[2] These legislators received scholarships covering their participation costs courtesy of the Seattle-based Scan Design Foundation, whose mission is to grow, develop, and encourage the relationship between the US and Denmark: www.scandesignfoundation.org

Working collaboratively, these legislators have led successful efforts in consecutive legislative sessions to make strategic investments to seed and grow IS in Washington. In 2018, the state commissioned a guide to industrial symbiosis to support economic development efforts in Raymond, WA. In 2019, the state commissioned a study to inform statewide IS policy development, which in turn led to the unanimous passage in 2020 of the nation's first statewide IS program – only to have it vetoed in the face of plummeting state revenues in the early days of the pandemic.

But legislators returned in 2021 to pass SB 5345, which was signed by the governor and launched the new IS program at the Department of Commerce. That program is providing grants "to expand existing industrial symbiosis efforts, assist others that are on their way, and support those still on the drawing board."[3]

In 2022, legislators increased funding for the new IS program, and in addition appropriated funds for WSU and partners to undertake this study of agriculture symbiosis opportunities for Washington.

Thanks to these strategic investments by the Washington State Legislature, agriculture businesses and entrepreneurs are increasingly inspired to expand and develop new symbiosis projects, and Washington is gaining international attention as the leading U.S. state for industrial symbiosis. In October 2022, CSI was invited to share Washington's IS story at the Global Leadership Conference convened by Kalundborg Symbiosis, which drew together some of the world's top IS practitioners.



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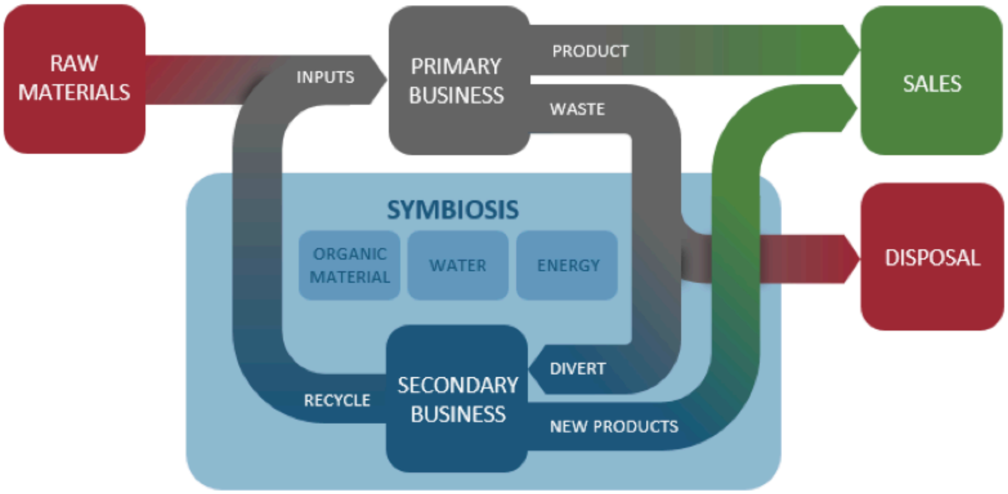
[3] choosewashingtonstate.com/wp-content/uploads/2022/10/Industrial-Symbiosis-Fact-Sheet-9-2022-1.pdf

III. Understanding Agriculture Symbiosis

At their heart, agricultural businesses such as farms and food processors take raw materials and add value to create products they can sell. **Agriculture Symbiosis** can add value for agriculture businesses by enabling them to reduce costs or generate new revenue by sharing surplus resources – energy, water, and organic 'wastes':



Major cost centers for agriculture producers include both the purchase of energy, water and organic resource inputs, and the costs to manage the waste flows resulting from production processes. Symbiosis agreements and infrastructure can enable businesses to profitably share surplus resources and reduce waste management costs. Of particular importance to agriculture can be projects to:

- Recover and recycle organic, carbon-rich wastes to generate clean resource products with market value, including energy, soil amendments, and high-value bio-chemicals, industrial feedstocks and compounds like proteins and polymers.
- Capture and recycle waste heat to displace fossil fuel purchases for process heat.
- Optimize and recycle wastewater to ensure water quality, extract organics for value, and generate clean water for reuse.

Symbiosis projects align well with the goals of increasing economic development and achieving environmental sustainability because they offer both a compelling business case for each participating company and deliver substantial sustainability performance improvements.

In this study, we identified two main categories of agriculture symbioses:

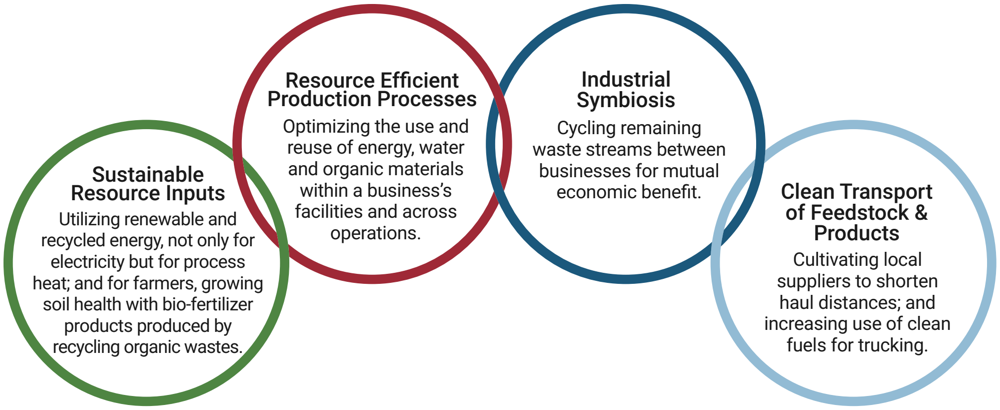
- **Business-to-Business Symbiosis**
  Agricultural businesses forge waste-to-value partnership agreements to share surplus resources for mutual economic benefit and environmental gains
- **Utility-Enabled Symbiosis**
  Clusters of 2 or more industrial facilities are served by symbiosis infrastructure that is financed and operated by one or more utilities, who ideally provide integrated services and support across multiple resources.

Most agriculture symbiosis projects in Washington that we identified in our initial scan are business-to-business (B2B) symbiosis projects, initiated and financed by the participating businesses. This contrasts with Denmark, where most symbiosis projects are financed, operated, and facilitated by the local utility provider, in cooperation with the industries they serve. When utilities take the lead, agriculture businesses are likely more willing to engage because they do not have to become expert in technologies and invest significant time and energy navigating the complexities of financing and developing multi-partner projects. But in the absence of utility leadership, B2B symbiosis projects, which tend to be smaller scale and less complex, can enable a few nimble business innovators to put projects to share surplus resources into operation and to expand incrementally into adjacent opportunities.

Industrial symbiosis is one of at least four key links in a '**Clean Industry**' supply chain by which businesses can improve sustainability performance and profits across their operations. These four key links include:

- **Sustainable Resource Inputs**
  Utilizing renewable and recycled energy, not only for electricity but for process heat; and for farmers, growing soil health with clean soil amendments and bio-fertilizer products produced by recycling organic wastes.
- **Resource Efficient Production Processes**
  Optimizing the use and reuse of energy, water, and organic materials within a business's facilities and across operations.
- **Industrial Symbiosis**
  Cycling remaining waste streams between businesses for mutual economic benefit.
- **Clean Transport of Feedstock and Products** –
  Cultivating local suppliers to shorten haul distances and increasing use of clean fuels for trucking.

This report focuses on the Industrial Symbiosis link in the Clean Industry chain, specifically its potential to benefit the agriculture sector. But projects that demonstrate a positive return-on-investment for agriculture businesses in any of these four Clean Industry categories will also improve sustainability performance across the overall food system's supply chains. And, of course, some projects will span links on the supply chain, for example, by shortening haul distances and enabling profitable symbioses.



IV. Agriculture Symbiosis: Examples in Washington & Beyond

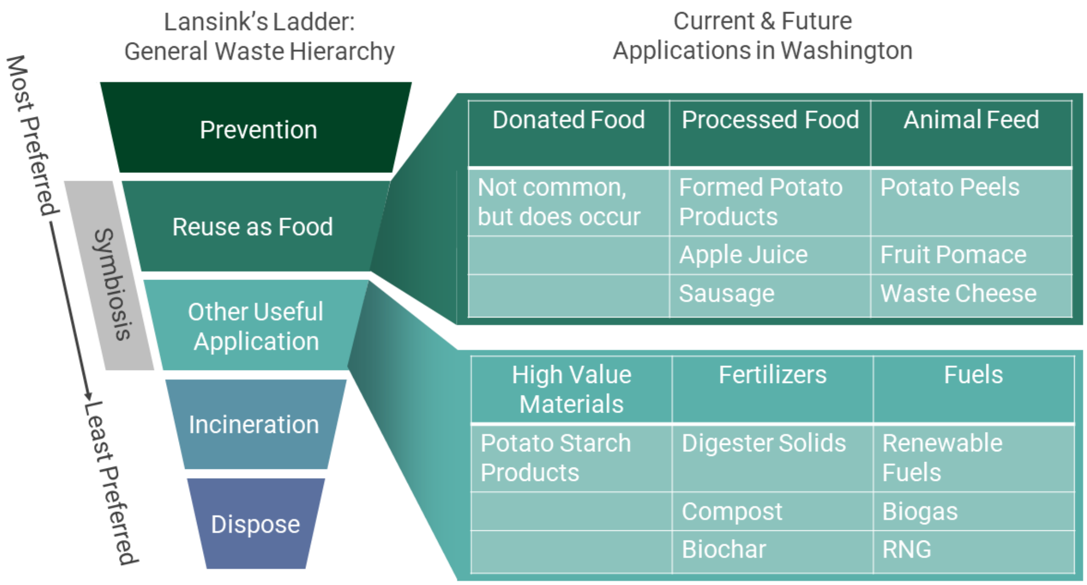
Our scan of agriculture symbiosis projects in Washington uncovered 18 illustrative projects that appear to meaningfully reflect IS principles and are in active operation or development.

Sprinkled through this report, are profiles of several of Washington's agriculture symbiosis project pioneers to provide a fuller picture of a diverse subset of the innovative projects highlighted in the table on page 10.

Industrial symbiosis is a new term for the agriculture sector in Washington, and several innovators we talked to have integrated symbiosis principles into how they do business without using this term to describe it. For this reason, ongoing systematic investigation would undoubtedly uncover other worthwhile projects.

Other examples of innovative agriculture symbiosis projects that are no longer in active operation were also discovered in Washington, underscoring the fact that these arrangements are business partnerships at their heart, and must generate economic value to remain viable. In some cases, other barriers also contributed. These barriers are more fully described later in this report.

Appendix D offers a compilation of successful industrial symbiosis projects from beyond Washington with significant agriculture sector components, selected to provide additional insight into the scope and scale to which agriculture symbiosis principles could be applied in Washington.



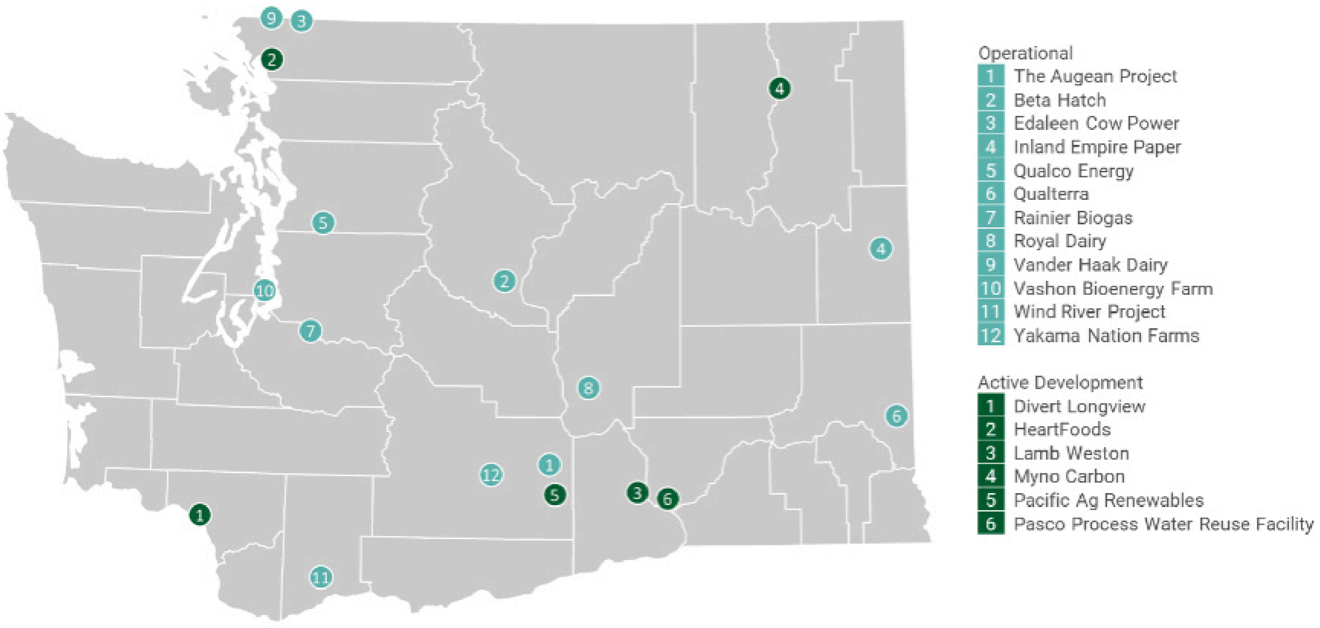
Donated Food	Processed Food	Animal Feed
Not common, but does occur	Formed Potato Products	Potato Peels
	Apple Juice	Fruit Pomace
	Sausage	Waste Cheese

High Value Materials	Fertilizers	Fuels
Potato Starch Products	Digester Solids	Renewable Fuels
	Compost	Biogas
	Biochar	RNG

Agriculture Symbiosis Projects in Washington State – Initial Scan

Projects in Active Development:

① **Divert Longview**	Longview	Divert works with grocers to reduce wasted food, and to divert remaining food waste from landfills to biogas production facilities that efficiently convert methane to a valuable renewable natural gas product. They are pursuing development of a facility in Longview to process food waste from up to 650 grocery stores across the Pacific Northwest.
② **HeartFoods**	Bellingham	Mark and Jessie Buehrer have launched HeartFoods to pilot a closed loop model for organic greenhouse agriculture that "utilizes food waste to transform how local communities grow healthy food." Their aim is to achieve net zero energy, water, and carbon while creating local food and jobs by cycling and optimizing flows of nutrients, water, and energy.
③ **Lamb Weston Plant**	Richland	Lamb Weston has committed to sell raw renewable natural gas made at its Richland site to Pine Creek RNG who will finish the gas before selling to Cascade Natural Gas along with RNG from Horn Rapids Landfill. Raw natural gas produced at Lamb Weston's Richland location is generated at their agricultural biogas recovery system and is currently being flared, but will be captured, processed and distributed through Cascade's system at the end of 2023.
④ **Myno Carbon**	Kettle Falls	Myno Carbon is developing a large-scale biochar carbon removal facility that will utilize forestry and mill waste residuals to produce 40,000 tons of biochar and 18 megawatts of carbon negative electricity per year, integrated with Avista's Kettle Falls Generating Station. They are also exploring combining waste carbon dioxide with crushed basalt to create a liming soil amendment.
⑤ **Pacific Ag Renewables**	Sunnyside	Pacific Ag Renewables plans to begin construction soon on a series of digesters to convert agricultural wastes – crop residues and dairy manure – into pipeline-quality renewable natural gas, and potentially other products like molded fiber packaging.
⑥ **Pasco Process Water Reuse Facility (PWRF)**	Pasco	The City of Pasco, in a public private partnership with Burnham RNG, broke ground in the second quarter of 2023 on a $137 million modernization and expansion of the PWRF to treat 2 billion gallons per year of industrial wastewater from seven major food processors. Anaerobic digestion will be the source for 900 million btu/day of pipeline-quality renewable natural gas, after which the growth of algae will remove nitrogen from the water so it can be beneficially reused for irrigating crops, and provide feedstock for a nitrogen-rich fertilizer product.



Operational Projects

1	**Augean Project**	Yakima	The Augean Renewable Natural Gas (RNG) project in Yakima County is producing pipeline quality RNG from the digestion of dairy manure from the DeRuyter & Sons and D&D Dairies. Benefits include greenhouse gas reductions, renewable transportation fuel, resource recovery including the production of biofertilizer and digested dairy fiber for use as cow bedding or as a peat moss substitute, and reclaimed irrigation water.
2	**Beta Hatch**	Cashmere	Locally sourced agriculture wastes, plus waste heat from a nearby data center, feed an insect farm that produces high-value proteins for animal food products. Insect wastes known as 'frass' are sold as a high-value fertilizer.
3	**Edaleen Cow Power, LLC**	Lynden	Edaleen Dairy recycles cow manure and pre-consumer food waste using anaerobic digestion to collect methane to produce electricity. As of 2022, they are generating enough clean energy to power 380 local homes. The emission-free electricity is sold into transportation markets to power electric vehicles. The system also produces soil amendment products and liquid fertilizer for Edaleen fields while assisting local food processers in treating their waste materials.
4	**Inland Empire Paper**	Millwood	Inland Empire Paper Company transforms their waste fly ash into a pelletized form that can be delivered to agricultural soils using conventional farm equipment. The fly ash neutralizes acidity and adds minerals to the soil, benefiting soil health and crop yields.
5	**Qualco Energy**	Monroe	Qualco Energy, a partnership between the Tulalip Tribes and Werkhoven Dairy, operates a dairy waste digester to save money and improve water quality. Snohomish Public Utility District uses the resulting biogas to run a generator and digestate from the process is utilized on farm fields, with nutrients that are more accessible to the farm's field crops.
6	**Qualterra Agriculture Regeneration Stations**	Pullman (HQs)	Qualterra designs biomass processing units that their agriculture industry customers can use to create 'Agricultural Regeneration Stations', integrated systems to process organic waste into biochar and renewable energy. A single unit can process 450 tons of biomass per year, resulting in 112 tons of biochar, and generating 30x more energy as an output than is required as an input. The company is partnering with Eastern WA farmers to conduct R&D both on-farm and from their research and production facilities in Spokane, Pullman, and Sunnyside.
7	**Rainier Biogas**	Enumclaw	Rainier Biogas collaborated with three family farms— Ritter Dairy, Wallin Dairy, and the DeGroot Brothers Dairy—to build a digester that serves approximately 1,200 cows. The project generates electricity, sold to Puget Sound Energy, and carbon credits that result from the capture of methane, a potent greenhouse gas.
8	**Royal Dairy**	Royal City	Royal Dairy cleans and recycles washwater from milking barns via a 7-acre BioFiltro worm bed made of locally-sourced wood waste. Developed in partnership with Organix, the worms not only filter water clean, but produce rich organic soil amendments that can enhance farm soils or help remediate brownfields.
9	**Vander Haak Dairy**	Lynden	Vander Haak Dairy installed Washington's first dairy digester in 2004. It converts manure and food waste from nearby food processors to produce renewable energy while capturing and using the methane. Digestate (solids and liquid fertilizer) can be used in animal bedding and crop production. The project was the first demonstration site for several emerging nutrient recovery technologies. The dairy partners with 15-20 food waste suppliers as well as the local municipality.
10	**Vashon Bioenergy Farm**	Vashon Island	Chomp (formerly known as Impact Bioenergy) is producing RNG from organic wastes generated by Island Spring Organics manufacturing plant, which is then used to power production processes at the facility. They also capture waste heat from the facility to heat the digester and manufacture certified organic liquid fertilizer.
11	**Wind River Project**	Carson	Wind River Circular Systems (a collaboration of Wind River Biomass Utility and Gorge Greens) creates value from waste wood by converting it to heat and power for year-round organic greenhouse food production. They also produce firewood, wood chips, and biochar from wood waste.
12	**Yakama Nation Farms**	Yakama Nation Indian Reservation	Yakama Nation Farms grows crops on 1500 acres, one third of which is certified organic. The farm produces compost from wood and fisheries waste. They are partnering with NW Harvest on a new storage facility and free food market that improves nutrition in their community. The Nation is working with EPA on the Columbia River Restoration and are exploring vermiculture for remediation with Perca, Inc. Others involved in these symbiotic remediation efforts include Save Family Farming and Salmon Safe.

City of Pasco Process Water Reuse Facility

The City of Pasco broke ground in 2023 on a $137 million modernization and expansion of its Process Water Reuse Facility to treat 2 billion gallons per year of industrial wastewater from seven major food processors.

PRE-SYMBIOSIS

Pasco's facility for treating and reusing wastewater from major food processing facilities faced multiple challenges:

- The treatment facility required expansion to be able to handle an increase of nitrogen loads that are projected due to the growth of the food processing industry.
- Aged-out infrastructure needed replacement.
- System data gaps limited whole-system efficiency.
- Business-as-usual solutions promised high capital and operating costs, high long-term energy demand, odor issues, and insufficient wastewater storage to support year-round food processing and corresponding job growth.

Instead of dispersing low-quality water over a larger area, innovators at Pasco Public Works re-examined the whole system, and developed a symbiotic network of solutions that capture value from waste, reduce reliance on fossil fuel and enable the creation of hundreds of jobs as new storage will make year-round food processing a reality.

BENEFITS

Expanded, year-round food processing; job creation in the hundreds; Darigold expansion; cost-effective regulatory compliance; value capture from wastewater (biogas and nutrients); better data, collaboration and system protocols; avoidance of costly SBR technology and high ongoing (polluting) power demand, local investment and construction jobs, model for others in the industry.

SYMBIOSIS IN ACTION

The City is moving forward with:

- Addition of Low Rate Anaerobic Digesters to capture methane gas from food processing wastewater to produce renewable natural gas.
- Close to 1.5 billion gallons per year of pre-treated water with some nitrogen will be used to irrigate crops, reducing the need for farmers to purchase fertilizers.
- Biological, low-energy nitrogen removal system uses algae.
- Marketable algae-based fertilizer is a resulting product.
- Creation of 300+ full-time jobs due to year-round capacity for food processing, plus construction jobs.
- Treating (and capturing value from) waste streams from new Darigold facility.
- Possible future inclusion of post-consumer food waste in anaerobic digestion.

Anaerobic Digesters and RNG Facilities

Rotating Algae Biofilm Greenhouse

KEY TAKEAWAYS

Emerging interest to capture nutrients can help decrease the cost of nitrogen removal treatment.	Good data and data-sharing are critical.	Lowering power need sets up decades of energy savings and pollution avoidance.	Innovative approaches take time, good data and good analysis.	Strong proposals with multiple benefits can attract significant funding.	AD technology allows for more and more ways to extract valuable energy from wastewater, enabling converting cost centers to value centers .

v. Key Findings of Consultations and Targeted Research

The WSU-CSI-PNNL project team combined several different approaches for the work summarized in this report.

Working collaboratively with the team, CSI conducted interviews, consultations, and site visits with experts, innovators and stakeholders from Washington and beyond, while WSU and PNNL researchers conducted several lines of targeted research to strategically expand our understanding of the agriculture sector's symbiosis opportunities and challenges.

Key findings from this body of work are presented in this section, in three subsections: Stakeholder-Identified Opportunities, Stakeholder-Identified Barriers, and Targeted Research.

Stakeholder-Identified Opportunities

Washington State Leads
Washington is already leading in industrial and agriculture symbiosis projects (see Section IV) that point to an opportunity-rich environment for growth and expansion of these pioneering projects.

Waste Presents Opportunities to Create Value
Agriculture producers can generate economic value and reduce costs by sharing and re-using water, heat, and organic materials. Experts recommend businesses take steps to optimize the efficiency and cycling of these resources within and throughout their own operations, and then use symbiosis projects to create value from waste streams that remain.

Symbiosis Infrastructure and Agreements Needed
Converting waste into new value for participating businesses requires infrastructure and symbiosis agreements that benefit all participants by producing new products and revenues or decreasing costs and waste.

Promising Opportunities Abound in Washington State
Waste heat recovery and recycling, harvesting value from organics-rich agricultural wastewater, enhancing soil fertility, and generating other high-value bioproducts from organic wastes are promising symbiosis opportunities for Washington agriculture.

Symbiosis Can Help Solve Thorny Problems
Symbiosis projects can in some cases provide new options to help solve persistent, statewide problems – such as orchard waste or logging slash that is now burned, wastewater overloaded with nutrients, volatile prices for synthetic fertilizer and natural gas, food waste, and climate pollution.

Equity
Clean industry investment by governments can be an effective way to advance equity goals because jobs in industry, manufacturing, and production are accessible to workers without a college degree yet tend to pay well. The jobs are also widely dispersed throughout the state, benefiting the full geographic sweep of Washington communities.

Utilities Can Help
Utility organizations can play a crucial role in facilitating and financing symbiosis projects and infrastructure, if creative, flexible new authorities to organize multi-resource, district-scale utility enterprises are available.

Stakeholder-Identified Barriers

Our consultations with experts, innovators, and stakeholders for this study surfaced a variety of barriers impacting agriculture producers' ability to fully realize profitable symbiosis opportunities. Here we have synthesized this input to distill five major barriers to overcome for agriculture symbiosis to thrive and grow in Washington:

Competing Priorities
Agriculture businesses are experts in, and focus primary attention on, delivering their primary merchantable products, not on state-of-the-art symbiosis infrastructure and solutions. As a result, they may not be aware of, or knowledgeable about, positive business opportunities for agriculture symbiosis projects.

Capital Squeeze
Agricultural businesses continuously must make hard choices over where to target scarce capital investment dollars. Many options have potentially positive return-on-investment, so proposed symbiosis and resource optimizing projects must compete with other proposed projects that may seem production-critical or have shorter 'payback' times. For businesses on the margins of profitability, capital dollars may be quite scarce, especially for projects that produce returns on investment over longer time periods.

Hedging Real and Perceived Risk
Implementing innovative new systems and processes can be riskier than the tried-and-true approach. Agriculture businesses often operate on narrow profit margins and are naturally reluctant to put their own capital at risk, especially on systems they are not expert in. Symbiosis participation needs to be easy and low-risk for agriculture businesses, but models to deliver easy, low-risk on-ramps to participate are still immature in Washington.

Utilities Have the Skills, but Not the Authorities
Utility organizations exist to bring expertise and patient capital to energy, water, and waste management, and so should be in a better position to deploy capital on symbiosis infrastructure that will benefit industry and sustainability. But U.S. utilities are quite siloed, hindering their capacity to deploy and manage multi-resource symbiosis infrastructure.

Funding Siloes Can be Blind to Integrated Solutions
State and federal incentive programs to improve the efficiency and sustainability of energy, water, and waste infrastructure are similarly siloed, targeting narrowly defined projects at the expense of integrated solutions that can maximize economic and sustainability benefits.

Targeted Research

To complement the findings from interviews, consultations, and site visits with experts, innovators and stakeholders from Washington and beyond, the team also conducted several lines of targeted research and analysis to strategically expand our understanding of the agriculture sector's symbiosis opportunities and challenges:

1. A Quantitative Assessment of Agriculture Symbiosis Opportunities
2. Technology Development Review and Evaluation of Benefits
3. High Level Review of Policy Context
4. Compilation of Select International Agriculture Symbiosis Projects
5. Overview of California's BEAM Initiative

Key findings from these five lines of targeted research are presented next, while detailed findings are presented in Appendices A through D.

1. Quantitative Assessment of Agriculture Symbiosis Opportunities

Refer to Appendix A for further information.

The *Quantitative Assessment Appendix* focused on identifying opportunities through sector-wide inventories and geospatial analysis to discern general solutions and symbiosis pathways with the largest overall potential impact. This analysis is useful for delineating opportunities for large corporate development or policy makers. This work consisted of several key steps, including creating a facility database with more than 1,000 entities involved in agriculture and food manufacturing, characterizing the supply chains of several of the state's most important agriculture products, and analyzing potential uses for waste biomass and heat.

KEY FINDINGS

Opportunities Vary by Location
The highest value agricultural supply chains are mostly concentrated in Eastern Washington. In particular, the Yakima Valley and Mid-Columbia Basin present attractive opportunities for symbiosis because they are home to both producers and processors. Supply chains for several commodities of interest like apples, potatoes, beef, and grapes are almost completely contained within this area while dairy also has a major presence. The Detailed Supply Chain Appendix describes where different feedstocks are produced in addition to other considerations like seasonality and competition from other users.

Technologies Must be Appropriate for Small & Medium Scales
Most agricultural commodities in Washington generate waste biomass that is a challenge to manage. Because this biomass typically has a high moisture content, transportation is expensive, particularly over long distances. Additionally, no single commodity is available at a large enough volume to support a facility that is dependent on a large scale to be profitable, like an advanced biofuels or biochemical manufacturer. Typically, these plants are most profitable at scales that use hundreds of thousands of tons of feedstock per year, which would place the demand for waste near the annual incoming capacity of many primary processing plants, let alone their waste output. The largest fruit processors use between 100,000 – 200,000 tons per year and the largest potato processors use between 200,000 – 450,000 tons per year. Reflecting this, emphasis should be placed on technologies such as anaerobic digestion and others that can accept a diverse range of feedstock throughout the year and be built at a variety of scales.

Re-use is an Important Component within Agricultural Waste Management
The default use for much of the waste from the Washington agriculture sector is focused on relatively low value uses that mitigate disposal costs. For instance, biomass is frequently sold for cattle feed, and much of the wastewater from fruit and vegetable processors is used to irrigate local fields during the growing season. Neither of these applications generate significant revenue and both are also subject to significant limitations. High moisture and low energy content in biomass like fruit pomace and potato trimmings cap feed rates in cattle rations. Use of wastewater for irrigation requires that the generating facilities be near irrigated fields. Irrigation can only be done during the growing season, and there are maximum levels of organic and inorganic materials that can be present in the water.

Low-level heat
As discussed in the Heat Sharing section of Appendix A, waste heat generated by most agriculture processors is low-grade, meaning it is difficult to capture and use compared to heat generated by other heavy industries. Despite this, waste heat from processors may be useful for several purposes like preheating water for steam, heating water for sanitation, supplying heat for biological processes like fermentation, and space heating. Some of the most likely customers of this low-grade waste heat within the agriculture sector include wineries, which maintain consistent cellar temperatures throughout the year and fish hatcheries, which use heat to encourage biological processes. Campus-style non-industrial facilities that use natural gas to heat their facilities, like college campuses and hospitals, may also be able to use waste for space heating.

2. Technology Review and Evaluation of Benefits

Refer to Appendix B for further information.

Based on the evaluation of potential biomass types and flows within our agricultural system, a literature review was conducted to explore anaerobic digestion and developments that might be applicable to agriculture symbiosis projects in Washington State and to evaluate the potential environmental and economic benefits of adopting those technologies in the near term and in the future.

KEY FINDINGS

Among existing, well-established technologies applicable to agricultural waste streams, anaerobic digestion (AD) offers great opportunities for agriculture symbiosis projects in Washington State. Through AD, wet organic wastes from food processors and manure can be converted to biogas which may be used to produce renewable natural gas (RNG). The subsequent use of the RNG not only provides a renewable energy source for combined heat and power (CHP) or as a feedstock for sustainable liquid fuels, but it also eliminates the emission of greenhouse gases (carbon dioxide or methane) from the decomposition of this waste.

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.

Agriculture symbiosis projects utilizing mixed waste streams have the greatest potential to maximize biogas production. For example, adding manure as a source of nitrogen to the fruit waste substrate may considerably increase biogas and methane yields. Alongside manure, supplementing lignocellulosic biomass (such as crop residues) to the fruit waste-manure substrate may result in yet higher biogas and methane yields. Biomass pretreatment prior to anaerobic digestion may be used to improve digestion yields.

Transportation is a key consideration for biomass, particularly wet wastes, because they are heavy due to the high moisture content, and are therefore costly to transport. 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 currently ranks 22nd of 50 states.

Agriculture symbiosis projects that use AD technology have the potential to generate capital investments, permanent jobs, and additional revenue within the agriculture 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-based natural gas, heat, and electricity. In some cases, climate benefits also result from reducing methane and carbon dioxide emissions from current waste management practices.

Among emerging technologies, hydrothermal liquefaction (HTL) presents potential future opportunities for agriculture symbiosis applications in Washington State. HTL, which is not yet commonly used at commercial scale, converts agricultural wet waste streams into biocrude and subsequently biofuels. HTL 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., bioconversion, fungi-based treatments, vermicomposting, microbial fuel cells and others, may be suitable for small scale opportunities.

Royal Dairy

A large, family-owned dairy worked with BioFiltro to establish a 7-acre worm-bed processing system for dairy wastewater.

PRE-SYMBIOSIS

- Greenhouse gases and ammonia are produced when wash water sits in dairy lagoons, the typical process for settling out solids when vermiculture isn't used.
- Additional water usage was required prior to recycling of dairy wash water.

SYMBIOSIS IN ACTION

- **Wash water** from milking barns is treated in the worm bed and reused on-farm
  - Liquids flows through large beds made up of gravel, wood chips, and worms — this cleans the water and reduces nutrients to the point where it can be land-applied or reused as wash water.
  - Once the wood chips are largely broken down, they are rich in worm castings and every couple of years the top layer can be harvested and used as a fertilizer that is full of beneficial microbes.
  - Wood chips are sourced from local "retired apple trees" which are traditionally burned.
- **Cows are fed a diet of 12 locally grown ingredients.**
  - Crops are rotated so that the cow's manure adds nutrients to the soil; a variety of cover crops keeps the soil in place. Crops are beneficial to carbon sequestration when combined with minimal tillage and effective manure management practices.
  - Cows are fed farm wastes that don't meet standards for human consumption: potato skins, apples, carrots and peas that are the wrong size.
- Symbiotic relationship with Allred family apple and cherry farms – "the soils and the ruminants and their byproducts, and the cover crops are all working together…"

BENEFITS

Removes odor and ammonia, and inhibits the production of greenhouse gases from dairy waste.

Produces an amendment that can be applied to regenerate soil health and help sequester carbon.

Removes 80% of nitrogen from wastewater and reduces phosphorous and other problem nutrients. Remainder can be applied to fields.

KEY TAKEAWAYS

Vermiculture can effectively reduce nutrients in dairy wastewater, prior to the formation of potent greenhouse gases that are normally produced in lagoons.

This technology is scalable and can work for large operations like Royal Dairy, as well as smaller ones.

3. Overview of Policy Context

Refer to Appendix C for further information.

To provide a better high-level understanding of where and how existing policies are shaping the development and implementation of agriculture symbiosis, the team summarized and contextualized some key elements of the policy landscape. The goal of this work was not to dig into the details of particular regulations, grant programs, or other support. Instead, the goal was to identify major areas in which existing policies are relevant to industrial symbiosis in the agriculture sector.

To identify the most important policy-related opportunities and barriers relating to agriculture symbiosis in Washington, the team summarized key policy lessons from the stakeholder interviews carried out by CSI. To place these insights into a broader context, the WSU team then reviewed recent Washington- and Northwest-focused road-mapping efforts related to specific industrial symbiosis technologies with agricultural applications for policy-related insights; key elements of the state policy landscape; and the academic literature relating to industrial symbiosis policy.

KEY FINDINGS

Agreement that Incentive-Based Programs are Key to Create Opportunity. Many current regulatory policies such as waste diversion laws and clean fuels programs have been praised by the stakeholders that were interviewed, including those in the agriculture industry, for helping catalyze agriculture symbiosis opportunities. However, there is broad stakeholder agreement that incentive-based policies would be most helpful in creating opportunity moving forward. Incentives play an important role in reducing risk that accompanies the implementation of new technologies and processes, and in reducing the need for high capital investments. Some stakeholders suggested that the state could continue and expand support for agriculture symbiosis projects through existing or new grant programs, while others had a variety of other ideas, including support for market development, for research and development activities more generally, or for feasibility studies. Incentives could be tailored to address existing issues in the agricultural industry while providing support for engaging in new forms of symbiosis. Stakeholders were clear that regardless of the type of incentive, it is essential that any programs are easy to navigate so that the opportunities are obvious to those in the industry.

A Role for the State to Facilitate Convening Opportunities in Support of Agriculture Symbiosis. Stakeholders suggested that a high priority need is a forum for those in the industry to convene with each other and with other stakeholders (government/agency, academic, non-profit) to exchange information, ideas, and best practices; identify common challenges and opportunities; and develop next steps where consensus exists. Incentives and collaborative opportunities can work hand-in-hand to reduce risk related to implementing new symbiosis approaches.

Rapid development of state and federal policy in the areas of energy, climate, and solid organics is supporting opportunities for agriculture symbiosis. Ensuring that these opportunities are realized may require better access; for example, some federal opportunities may be unclear or difficult to navigate. It will also require understanding where alignment (or realignment) of policy at multiple levels can ensure greater returns and greater impacts for symbiosis innovation. For example, the recently passed HB 1799 requires the diversion of organic material from the landfill. As local jurisdictions and businesses begin recovering this post-consumer waste, an opportunity may exist to create low-carbon energy such as renewable natural gas or liquid fuels. Local jurisdictions could consider collaborating with nearby industrial facilities to promote symbiosis opportunities. These collaborations can ensure these renewable energy facilities can obtain the feedstock necessary to create low-carbon fuels. Likewise, local jurisdictions could review their organic waste disposal requirements for business and residences, to ensure that they encourage, rather than discourage or prevent symbiosis opportunities.

Business-as-usual regulatory language and processes can limit innovation and can be a particular barrier for newer agriculture symbiosis technologies. Because almost all symbiosis projects include industrial facilities, some of them quite complex, developing projects need to navigate existing regulatory requirements. This often includes (but is not limited to) air and water quality permitting, and sometimes solid waste permitting or water rights/water supply. Permitting needs and pathways can be unclear for newer technologies (i.e., those that are not business-as-usual), and this can create delays, added costs and added uncertainty. Regulators – as well as those implementing agriculture symbiosis projects – have an important interest in ensuring the protection of both public and environmental health. And yet facilitating efficient pathways for appropriate oversight and permitting is a key need.

Ensuring policy coordination and alignment is helpful. The web of policies that encourage or discourage agriculture symbiosis projects is highly complex. Agriculture operates within multiple policy areas, including renewable energy, air, water, climate, organic solid waste management, and soil health. These policy areas have historically developed separately, with little attention paid to the connections between them. At the state level, there are few explicit mentions of symbiosis in policy, and most current policies have a more singular focus (e.g., promoting biofuel production). Many symbiosis relationships are maximally beneficial when resources are transformed (e.g., organic waste to energy, wastewater to fertilizer, etc.) and transferred across sectors, but navigating across siloed policy areas can be difficult since policies may be misaligned, explicitly or implicitly prohibitive, or unclear.

Sustained symbiosis thrives when there are both private economic and public policy incentives designed to perpetuate transactions. A range of existing policy analyses, and Washington's experiences with various technologies, suggest that economic benefits must be sustained in order for industrial symbioses to persist over time. As markets and incentives change, symbiosis projects may need to pivot or generate different products to remain viable. Within this context, policy does have a role to play in encouraging industrial symbiosis, especially for new areas and new technologies that are likely to be economically viable long-term but may have significant up-front costs. In this case, incentives play a role in reducing and rewarding the risk assumed by the early adopters.

4. Compilation of Select International Agriculture Symbiosis Projects

Refer to Appendix D for further information and additional examples.

Our global scan of relevant agriculture symbiosis examples resulted in profiles describing what we think are the most interesting case studies that may hold lessons for Washington practitioners.

KEY FINDINGS

Denmark's decades-long history and the nation's ongoing focus on improving symbiosis cooperative agreements and technical expertise has resulted in a variety of projects where agriculture-relevant waste byproducts are re-purposed by the agriculture sector and other industries:

- Solrød Biogas utilizes more than 190,000 tons of biomass feedstocks annually from local industry waste streams. They process pulp, pectin, and carrageenan from biotech processers as well as manure from local farms to produce heat and electricity to replace fossil fuels. Their processes also result in non-fossil fertilizers.
- GreenLab Skive, a 'green energy park of the future' is producing clean heat, animal proteins, electro-fuels, and other products from agriculture and other waste streams at, as of this writing, five private industrial facilities. Investment to date totals over $400 million. A noteworthy organic input, invasive starfish, is featured in Danish Marine Protein's process to produce supplemental protein for animal feed.
- Kalundborg Symbiosis, one of the oldest examples of symbiosis in the world, is located in the City of Kalundborg in Denmark. It is estimated to save the city $28 million annually by recycling water, energy, and materials between the 16 participating public and private entities. Together these partners offset 600,000 tons of carbon dioxide emissions annually. They are supported by a local multi-utility that directs the flow of water, wastewater, district heating and other resources.

Other nations across Europe feature advanced agriculture symbiosis operations:

- United Kingdom's British Sugar factory in Wissington is one of the largest beet sugar operations in Europe. They strive to utilize all waste byproducts, and methane generated from anaerobic digestion provides fuel to a combined heat and power plant, which provides carbon dioxide to a horticultural complex.
- Sweden's Sotenäs Municipality in Gothenburg converts organics, including aquaculture waste from fish farms, into fertilizer and biogas. Other aquaculture byproducts serve as inputs for production of algae onsite.
- Germany's Biowert Biorefinery, near Frankfurt, converts grass to biobased plastics while producing renewable energy and biofertilizers as coproducts.

South Asian and East Asian nations are making significant progress developing agriculture symbiosis partnerships, but English-language resources describing their operations are limited.

- In India's Nanjangud Industrial Area, located in a region that is rich with sugar and coffee producers as well as other farms, 45 companies have partnered to collectively process 900,000 tons of organic waste residues. It is estimated that 99.5% of residuals are recycled at least once.
- China's Guitang Group in the Guangxi Zhuang Autonomous Region leverages sugar cane residue to produce paper, alcohol, calcium carbonate, cement, and power.

Vashon Bioenergy Farm

Chomp, formerly Impact Bioenergy, has invented a small-scale, modular anaerobic digester and deployed a pilot system at a tofu factory on Vashon Island.

PRE-SYMBIOSIS

- Disposal costs were higher because organic waste was transported off-island; more fossil fuels were needed for heat and powering trucks.

SYMBIOSIS IN ACTION

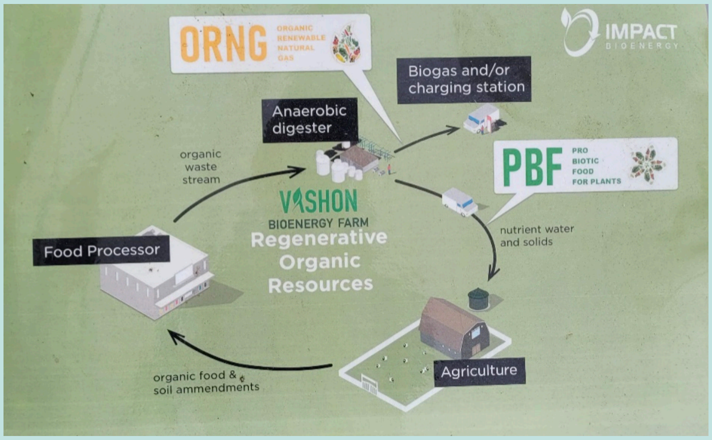
- The pilot system at Vashon Bioenergy Farm transforms the waste from Island Spring Organics tofu production process into an organic liquid fertilizer and ‘organic’ renewable natural gas (ORNG) that replaces natural gas on-site or in vehicles.

SYMBIOSIS IN PROGRESS

- In coordination with Zero Waste Vashon, Chomp is considering a bigger aerobic/anaerobic system for collecting additional organic waste from the community (commercial, residential and farm waste) to process on-island and reduce the need to transport waste off-island.

BENEFITS

- Reduces fossil fuel inputs and costs in heat and transportation; increases organic waste recycling; creates a marketable product, organic liquid fertilizer, that can offset the use of fossil-based fertilizers; generates ORNG for on-island use.
- Reduces greenhouse gas emissions by diverting organic waste from landfills: avoids trucking and transportation emissions and results in ORNG production on-site rather than methane escaping from landfills.
- Decentralized systems offer resilience and energy independence.
- These circular, closed-loop systems turn food waste into renewable energy and organic biofertilizer to grow more food.



KEY TAKEAWAYS

- Anaerobic digestion (AD) is feasible on a community scale.
- Anaerobic Digester systems can offset the cost of waste management for smaller food processing businesses by converting moderate waste streams to value.
- Liquid digestate from AD can be used as an effective fertilizer.
- Marketing innovative new products (like microbial fertilizers) is challenging.
- Sales of RNG for vehicle fuel can be more economical than displacing on-site natural gas usage.
- Creating close-looped systems in hard-to-reach locations, such as islands, can greatly alleviate costly transportation and associated emissions.

5. Overview of California's BEAM Initiative

The North San Joaquin Valley's BioEconomy, Agriculture & Manufacturing (BEAM) Initiative in California provides an agriculture-centered innovation cluster model that can inform thinking for a Washington agriculture symbiosis initiative. This overview provides an introduction to the genesis and structure of BEAM, but further investigation and knowledge exchange can more fully reveal lessons learned and their applicability to supporting agriculture symbiosis in Washington, as suggested in Recommendation #3 in the following section of the report.

The BEAM initiative grew out of an effort to build ***"a regional economy that is more diverse, inclusive, connected, vibrant and resilient,"*** and that identified bioindustrial manufacturing as its key strategy to achieve those goals.

Bioindustrial manufacturing has strong overlap with agriculture symbiosis, in that both are about repurposing wasted or underutilized organic resources, often amongst multiple companies, to generate higher economic value with corresponding environmental and social benefits. A literature review and interview with their executive director highlighted several relevant challenges they face and the strategies they are using to address them.

KEY FINDINGS

A backbone organization that provides a clear locus of effort and direct assistance is critical to overcoming barriers to biomanufacturing. The initiative is driven by such an organization, called BEAM Circular, that serves as the ongoing "innovation engine" to advance and sustain bioindustry in California's agricultural hub.

Siloed, targeted regulatory and funding programs can create barriers to projects that involve multiple parties, span siloes and offer multiple benefits. BEAM provides sustained support for identifying and addressing regulatory barriers to bioindustrial manufacturing, which relies on sharing waste streams and converting them to value.

Emerging carbon markets and ESG (environmental, social and governance) investments offer access to new capital, but only with certification and validation services that can prove project performance across specific criteria, including decarbonization. BEAM provides access to certification and validation services that help companies prove triple-bottom-line project performance to investors and public agencies, facilitating private and public investment and bringing the initiative to scale.

Addressing skills development and lowering non-skill barriers to jobs and training (e.g., childcare, transportation) among the workforce, particularly in rural communities, will increase the skills and economic mobility of workers and drive inclusive economic development. As these services flow to some of the state's most disadvantaged communities, they can help expand access to opportunity and address geographic and racial disparities for workers, their families and communities.

"Startup accelerator services" are offered by BEAM to help individual businesses grow, as is common to many economic development strategies. BEAM will offer the following accelerator services to ramp up bioindustrial manufacturing:

- Technical advice and mentorship
- Access to testing and research facilities
- Curated connections to potential customers and investors
- Shared services like marketing support
- Post-accelerator services for alumni firms designed to encourage companies to stay and grow in the region, such as assistance identifying space and recruiting employees
- A Center of Excellence to provide ongoing locus of effort

VII. Recommendations for the Washington Legislature

This section provides recommendations for increasing the economic value and sustainability of Washington's agriculture sector through the use of industrial symbiosis principles. Because the scale and economic value of the agriculture sector in Washington is so large, the potential for economic benefit and value creation from sustainable resource recovery from the sector's energy, water and organic waste streams is also large in scale. The recommendations offered here, therefore, are designed to give lawmakers options to stimulate large-scale economic and sustainability benefits in the agriculture sector.

The four key recommendations:

1. **Coordinate and invest in agriculture symbiosis programs** in concert with others supporting clean industry
2. **Support market accelerator research** targeting key opportunities for agriculture symbiosis
3. **Help key state programs and industry to strategically align services** to support agriculture symbiosis innovators
4. **Forge collaboration agreements with countries and states** who are symbiosis innovation leaders

RECOMMENDATION #1

Coordinate and invest in agriculture symbiosis programs, in concert with others supporting clean industry

Why this recommendation?

- Agriculture is very important to the state's economy. The opportunities to optimize resource use and reuse to benefit both the bottom line for producers and their sustainability performance appear to be very significant, but still largely untapped.
- Several key barriers constrain the ability of Washington innovators to develop agriculture symbiosis, including competing demands for scarce capital for upgrades and lack of experience with symbiosis technology and processes.
- Washington state boasts a wide range of programs and investments to advance the clean industry supply chain, many of which have direct relevance to agriculture symbiosis. To the extent these wide-ranging programs are dispersed in state government, they can be more difficult than necessary to access for proponents of integrated, multi-resource projects.
- State grant investment targeting innovative projects can be a powerful catalyst for private investment, tipping the balance to enable value-generating projects to leapfrog barriers and pencil out for all parties involved.

This recommendation suggests lawmakers consider ways to:

- **Coordinate** symbiosis programs with others designed to support clean industry, and
- **Invest** targeted slices of the state's clean energy and climate funds for symbiosis projects.

COORDINATE

Washington state policymakers, recognizing the benefits of supporting the clean industry supply chain (see Section III), have adopted a wide range of programs and investments in recent years, across various segments of clean industry. Many of these programs have direct relevance to agriculture symbiosis. These segments range from organics recycling to renewable natural gas, sustainable aviation fuel, renewable hydrogen, bioproducts, industrial energy efficiency, sustainable farms, and more. In some but not all segments, policymakers have adopted framework legislation to strategically coordinate and focus state policy and investment in a particular segment. (see Summary of Policy Context in Appendix C).

With so many state programs to support different clean industry segments, agricultural and food processing companies may not realize that such opportunities are relevant to them, and proponents of agriculture symbiosis and related projects may find widely dispersed state programs and functions difficult to navigate. Legislators could help by investing in a one-stop shop for clean industry projects to access state financial and technical assistance, and to help leaders of key state programs coordinate delivery to better support great projects to overcome hurdles and advance toward fruition.

Symbiosis projects face unique barriers because they connect separate companies for mutual benefit, but forging these links is not in anyone's job description. Symbiosis enables companies to look across market segments at the whole supply chain to identify synergies that can optimize economic benefits and sustainability performance. But for many companies, the pressures of achieving profitability within their niche consume most of their attention.

A single point of state government contact to access assistance and support can make it much easier for symbiosis project proponents to benefit from state support. Valuable services could include:

- Helping project proponents to navigate the complex landscape of regulations, incentives, and permitting, and access the full range of funding sources for which projects are eligible.
- Providing a 'case bank' of successful symbiosis projects, and benefit-cost analyses to help participants make go/no-go decisions on specific technology investments.
- Offering skilled symbiosis facilitation services to help separate companies forge resource-sharing partnerships for mutual economic benefit.
- Helping projects commission highly-credible third-party performance evaluation to show public and private investors the economic and environmental returns on investment in such projects.

INVEST

Additional public investments in agriculture symbiosis could help to address stakeholders' wishes for a more incentive-based approach to symbiosis. These can act to de-risk projects through guaranteed payouts over multiple years, and/or reduce initial start-up costs for innovative symbiosis projects. State investments could also position Washington's symbiosis innovators to attract private investment and better compete for federal funding, which often requires matching funds.

Other regions and countries have had success in stimulating innovation in agriculture symbiosis projects through targeted investments. In addition to the BEAM Initiative in Central California, several international examples are described in Appendix D.

Washington has a history of incentivizing technology innovation in targeted areas to stimulate strategic sectors and opportunities, and the state is already a national industrial symbiosis leader. The 2021 Legislature adopted the nation's first statewide IS program, and appropriated a $2 million funding pool for the 2023-2025 biennial budget. The Department of Commerce is distributing these funds through competitive grants, with demand (reflected in applications to the IS program) already outstripping available funds.

To scale up state support for symbiosis and the clean industry sector broadly in Washington, policymakers could consider carving out symbiosis and clean industry programs within the state's two biggest, most directly relevant funding programs. The Clean Energy Fund (CEF) and the Climate Commitment Account (CCA) are both designed to speed Washington's transition to zero climate pollution by scaling 21st century clean technologies, while growing Washington jobs and businesses in the clean economy.

Examples of existing targeted carve-outs programs include the Rural Clean Energy Innovation Fund ($4.9 million in early 2023) and the Research, Development, and Demonstration Program ($8.5 million in 2022). Program carve-outs like this can advance innovation and help Washington organizations to attract federal and other matching funds.

Although agriculture symbiosis projects are eligible for some CEF and CCA funding, a more targeted approach to invest in the agriculture sector could help bring visibility and coordination to this emerging approach. This approach would also benefit a fuller geographic sweep of Washington communities, many of whom face persistent barriers to success. Because agricultural waste resources are dispersed through many parts of the state, the jobs and economic benefits from investing in agriculture symbiosis will be distributed statewide as well.

Lamb Weston Richland

Lamb Weston's Richland plant processes organic waste to produce renewable natural gas (RNG) that will be captured, processed, and distributed. The company also internally reuses water, heat and RNG at other facilities.

PRE-CIRCULARITY

- Raw natural gas produced at Lamb Weston's Richland plant is generated at their agricultural biogas recovery system and is currently being flared.
- Water and heat demands are substantial and required significant resources prior to implementation of circular practices in Oregon, Louisiana, and Minnesota facilities.

CIRCULARITY IN PROGRESS

- Lamb Weston has committed to sell raw renewable natural gas (RNG) made at its Richland site to Pine Creek RNG who will finish the gas before selling it to Cascade Natural Gas along with RNG from the nearby Horn Rapids Landfill.

CIRCULARITY IN ACTION

- At some of LW's other facilities outside of Washington (including those in Delhi, Louisiana and Park Rapids, Minnesota) RNG is captured and reused internally. Process water treatment at these plants includes anaerobic digestion, using potato waste to create renewable natural gas, which is used as fuel for each site's boilers, thus offsetting fossil fuel use and lowering carbon emissions.
- Another example of internal reuse of resources that is closer to home can be seen in the Hermiston, Oregon plant's state-of-the-art water reuse system. Process water is treated through anaerobic and aerobic processes and then treated for reuse using ultrafiltration, reverse osmosis, and disinfection processes before being returned to the production process.

BENEFITS

- In Richland, Lamb Weston's agricultural biogas recovery system and the landfill are expected to produce more than 2.5 million therms of RNG annually, displacing the need for fossil fuel based natural gas. This volume is enough gas to serve approximately 4,173 Washington homes each year with renewable fuel.
- In Hermiston, their water reuse system supported the expansion of the Hermiston operation, allowing them to add an additional production line without using any additional water . Clean water leaving this site is used to irrigate neighboring farms, delivering value for growers while reducing demands on local water supply.

RECOMMENDATION #2

Support market accelerator research targeting key opportunities for agriculture symbiosis

Why this recommendation?

Targeted research can play a role in accelerating the deployment of new technologies and growth of industrial symbiosis, contributing to Washington's leadership in this space.

Examples of the types of targeted research that could accelerate agriculture symbiosis markets and that were identified through research and consultations include:

- Forest products symbiosis
- Capture and recycling of industrial waste heat
- Multi-resource, utility-enabled Symbiosis Innovation Districts
- Development of new markets and products derived from organic wastes
- Documenting the benefits provided by agriculture symbiosis strategies

This recommendation could leverage current efforts at some of Washington's top research institutions. For example, Richland sits at the intersection of the state's agricultural and energy sectors. It is also home to the newly established WSU Tri-Cities Institute for Northwest Energy Futures (INEF). INEF emphasizes a system-level approach to decarbonization of energy and recognizes that adapting industry and agriculture is a critical component of this goal. Pacific Northwest National Laboratory's (PNNL) Process Development Units have long been used to research HTL (hydrothermal liquefaction), a process that converts wet wastes, like manure, biosolids, or food waste, into crude-like oil that can be used as a petroleum replacement. Additional efforts from these institutions and others can provide interdisciplinary expertise in areas spanned by agricultural symbiosis like water, organics and carbon cycling.

Five specific opportunities to accelerate symbiosis markets through strategically targeted, interdisciplinary research emerged from this project's consultations and research, including:

1. Forest products symbiosis

Like the agriculture sector, forest products facilities use significant volumes of heat, water, and organic material resources, and in the process often generate significant heat, water and organic waste streams. As with agriculture, they also face daunting logistical challenges in moving heavy waste products over significant distances, posing added challenges to capturing value from waste.

Many key barriers and solutions for agriculture identified in this report can be adapted to benefit the forest products industry. But important differences between agriculture and forest products resource inputs and waste streams can inform follow-on market accelerating research. For example, the volumes of woody wastes managed by the forestry sector tend to be much larger than organic wastes in the agriculture sector. Processing forest products may be more heat-intensive than many food processing operations. Woody wastes are mostly drier than the primarily wet wastes from agriculture. The crisis of forest fuel overloading across large swaths of Washington's forestlands, and planned forest health treatments, may dramatically increase the supply of forest waste requiring processing for years to come.

2. Capture and recycle of industrial waste heat
A primary use of energy for industry is for heating and cooling, but inadequate attention has been paid to understanding and developing cost-effective strategies to decarbonize industrial heat globally, nationally, and in Washington. New research in the European Union, led by Denmark's Aalborg University, found that waste heat is "the world's largest untapped energy source," and that available waste heat in the EU is nearly equal to total EU-wide energy demand for heat and hot water.

The Heat Sharing section of Appendix A provides a high-level assessment of heat sharing opportunities and technologies applicable for the Washington agriculture industry. A market accelerator research initiative could expand on this work by focusing initially on the agriculture and forest products sectors by mapping industrial heat demand and recoverable waste heat flows at a more detailed level, and identifying locations with concentrations of resource-intensive facilities where greatest near-term economic and sustainability gains can be achieved through sharing of waste heat. The Northwest Combined Heat-and-Power Program, a US Dept of Energy initiative, housed in WSU's energy program in Olympia, possesses invaluable expertise that can be tapped to support this research initiative.

3. Investigation of multi-resource, utility-enabled Symbiosis Innovation Districts
Industrial facilities in close proximity all require resource inputs and waste management systems. Utilities exist to bring expertise and patient, low-interest capital to energy, water, and waste management, and, in theory should be positioned to develop and operate symbiosis infrastructure and services that serve clusters of industrial facilities. But most U.S. utilities are quite siloed, required to focus on just one or two of the several resource inputs and waste services needed by industry. Utilities that are strictly siloed are poorly equipped, and often constrained by regulation, in deploying and managing multi-resource symbiosis infrastructure. Dealing with multiple, siloed utilities across an integrated industrial network presents yet another barrier to industries seeking to strengthen their bottom line through symbiosis.

Market accelerating research can inform lawmakers on options to update existing laws that authorize providers of energy, water, and waste services, including cities and counties (Title 35), port districts (Title 53), public utility districts (Title 54), and other utilities (Title 80). Researchers can analyze how these laws might be adjusted to expand allowed services to include all those needed by industry and key to symbiosis, from district heat and cooling, to recycling of waste and wastewater, to carbon management. They could also look at options to explicitly authorize Symbiosis Innovation Districts that leverage the strengths that utilities bring, while enabling more flexible, nimble, efficient, multi-resource utility enterprises that can develop richer, integrated symbiosis opportunities and infrastructure.

4. Development of new markets and products derived from organic wastes
Beyond energy, industrial symbiosis technologies can potentially generate a range of other products from organic wastes, while addressing both resource and energy flows. These can include clean soil amendments, along with other products, ranging from biochars, to specialty chemicals and functional fillers for polymers, lubricants, proteins for livestock, fish, pets or humans, and building materials.

Myno Carbon Kettle Falls

Myno Carbon is building a large-scale biochar production facility integrated with Avista's Kettle Falls Generating Station.

A Washington startup that aims to build large-scale carbon removal facilities that profitably remove and sequester carbon to mitigate the climate crisis and meet the needs of industry partners. The facility will intake wood waste from several sources and convert it into biochar, and also convert waste heat into renewable electricity.

SYMBIOSIS IN ACTION

- **Biochar production** converts wood wastes from timber slash and mill residuals into biochar, which is in turn used as a soil amendment to be applied to agricultural lands and forestlands.
- **Waste heat** from biochar production is used to pre-heat water for steam generation of renewable electricity at the Avista generating station.
- Myno is exploring utilizing the biogenic **gas emissions** to weatherize basalt as a secondary soil amendment.

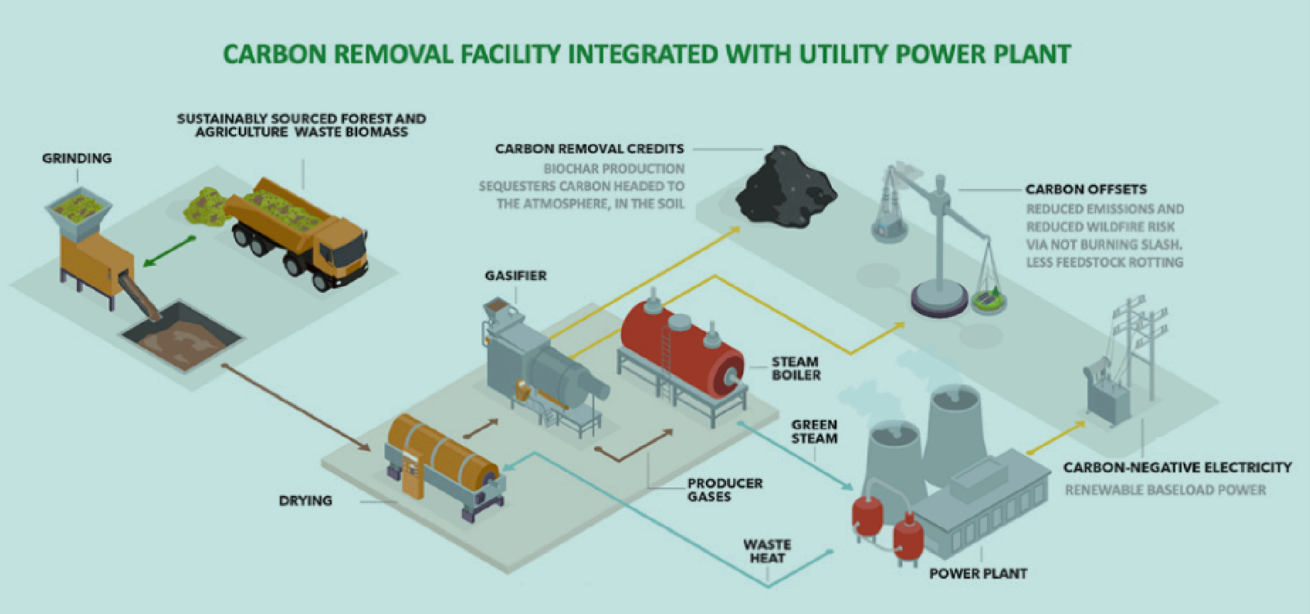
SYMBIOSIS IN PROGRESS

- **Renewable electricity** generated from steam using waste heat can be used to electrify heavy duty trucks, reducing transportation emissions.
- **Biochar** can be sold as direct-to-consumer products and generate carbon reduction credits as well as support the decarbonization of other industries.
- Efforts to work with WA DNR, USFS, and tribal partners, including the Colville Tribes to procure additional feedstock from forest health treatments (forest thinning waste) will come online in the next few years.
- No agriculture feedstock is planned for the facility, but they will explore opportunities as they arise.

BENEFITS

When applied to soil, biochar sequesters carbon dioxide and reduces nitrous oxide emissions. It also helps retain more water and nutrients in the soil, requiring less fertilizer be purchased and reducing emissions from fertilizer production.

Biochar production can sequester carbon from forest waste rather than slash pile burning, reducing greenhouse gas, toxic emissions, and wildfire risks.



KEY TAKEAWAYS

Co-locating biochar production at a power-generating station unlocks many efficiencies, including the ability to capture waste heat generated during biochar production for power generation.

Washington's farm and forest lands produce huge quantities of biomass that can be put to higher value use, with the primary bottlenecks being logistics and transportation.

Higher value products (on a pound-for-pound basis) can provide profitable – though often smaller – markets, that can enhance profitability for some symbiosis projects. Applied research can support market development for such products by helping demonstrate performance, addressing user questions, and providing guidelines for use for new bioproducts. State investment in bioproducts innovation can attract federal investment, which has recently ramped up in this area, particularly at USDA and DOE.

5. Document the benefits provided by agriculture symbiosis strategies
Agriculture symbiosis relationships offer both economic and environmental benefits, and in many cases corresponding social benefits. Delineating the various benefits of these projects helps these entities showcase their contributions to stakeholders, funding agencies and the public, and enables comparison to other models that can inform wise policy decisions on programs and funding. It can also encourage others to adopt these newer approaches, based on sound, common sense science.

Over time, credibly measuring costs and benefits of agriculture symbiosis will inform and help projects excel at optimizing economic, environmental and social performance. State investment in these efforts can also spur additional technology development aimed at maximizing benefits alongside improving economics.

Edaleen Cow Power

A key example of in-house circularity using anaerobic digestion (AD)

PRE-CIRCULARITY

- Manure and its nutrients are valuable byproducts from the dairy farm that were not being fully utilized.
- Costs and environmental concerns resulting from chemical fertilizer use
- Wood shavings used for cow bedding grew more expensive and harder to find when housing construction slowed in the region.

CIRCULARITY IN ACTION

- Dairy farmers are the original recyclers; producing a product, milk, and using byproducts, manure, to fertilize crops to feed back to cows to produce more milk, and more manure, to continue the cycle.
- Anaerobic digestion efficiently produces and captures biogas from the manure, then a system of solids separation extracts fibrous materials for re-use as cow bedding. Any remaining solids are land-applied to crops. The digester allows the farm to capture the biogas from manure to be used for renewable energy, advancing the farm's historical practice of recycling.
- Remaining liquid is treated to produce a stackable, truckable, phosphorous-rich solid to be used as fertilizer and a liquid that has a significantly reduced and well-balanced nutrient concentration.
- In 2022 the AD system required new investment to keep it maintained and operational. 3Degrees, a renewables and decarbonization firm, agreed to finance the project, and is now selling the digester electricity into transportation markets and capturing clean fuel standards credits.

BENEFITS

- Reliance on chemical fertilizers is reduced when AD nutrients are land-applied.
- There is no more need to purchase and transport cow bedding.
- Results in carbon-free electricity production.
- The system allows for a fine-tuned nutrient management process.
- After ten years the digester has supplied enough emission-free electricity to power 380 local homes while improving climate, air, and water quality, according to Bryan Van Loo of Regenis, who operates the AD for Edaleen.

KEY TAKEAWAYS

Large AD systems incur maintenance costs as they age, but there are innovative new financing options to extend renewable energy production with existing infrastructure.

Dairies can make good use of AD byproducts on-site, including fibrous materials and phosphorous-rich solids for fertilizer.

RECOMMENDATION #3

Help key state programs and industry to strategically align services to support agriculture symbiosis innovators

Why this recommendation?

- While symbiosis offers economic advantages, its implementation presents barriers that individual businesses are often ill-equipped to overcome. Symbiosis is about finding higher value through new networks, partners, technologies and shared infrastructure, and establishing symbioses may often take businesses beyond their capacity or areas of expertise and control.
- Securing capital investment to support less established, multi-party approaches like industrial symbiosis can be a constraint. An effective backbone organization can bring a variety of tools to overcome barriers and facilitate public and private investment.

This study has revealed multiple opportunities across Washington to use symbiosis to create new earnings and multiple benefits in the ag sector. But it has also identified challenges. The nature of symbiosis is such that individual companies are often ill-equipped to unlock the potential of innovative, value-adding resource exchanges between multiple companies or sectors. Successful symbiosis relies on new networks, partners, technologies and often shared infrastructure and utility services.

An example can be found in Pasco, where food processors initially received recommendations to use algae for denitrification of their wastewater with some skepticism. They had no knowledge of this technology and perceived it to be unproven, and so were concerned about exposing their companies to excessive risk. The City, who processes these companies' wastewater, likewise had no algae expertise. A modest $50,000 grant from Commerce's Industrial Symbiosis grant allowed the City to dig into and ultimately decide on algae as an effective, proven treatment option. Algae will require significantly less energy over the multi-decade life of the infrastructure, produce a fertilizer as a marketable product, and save money for processors and ratepayers. Without this external support, this symbiotic opportunity would have remained hidden from view.

While motivated entrepreneurs are finding ways to overcome the barriers to profitable symbiosis in some instances, addressing them in more systematic ways will make broader adoption faster and easier.

Washington has been pursuing an "innovation cluster" approach in recent years through the Department of Commerce's Innovation Cluster Accelerator Program (ICAP) to "help promising industry sectors assemble the ingredients they need to grow, such as access to capital, the latest research and support for entrepreneurs." While ICAP offers a viable approach, additional funding for the program would be needed to add any clusters beyond the nine existing designated clusters.

In considering options for providing the kind of "backbone" support offered by cluster organizations, an informative example can be found in California's BEAM Initiative (BioEconomy, Agriculture & Manufacturing) in the agriculture powerhouse region of the North San Joaquin Valley. The BEAM Initiative arose from an American Rescue Plan Act (ARPA)-funded process committed to building *"a regional* *economy that is more diverse, inclusive, connected, vibrant and resilient"* that identified bioindustrial manufacturing as its focus. A cross-sector working group of industry, government, academic, and community leaders (including former USDA Director Ann Veneman) developed a multi-faceted ecosystem strategy to provide the structure, capacity, and momentum to build an effective innovation engine for bioindustrial manufacturing. The benefits of the proposed innovation engine are intended to flow to some of the most severely disadvantaged communities in California.

As with the BEAM Initiative, agriculture symbiosis also sits at the intersection of agriculture, manufacturing and the bioeconomy, so this nascent initiative can likely provide helpful lessons as Washington explores how it can best support symbiosis as a means of increasing the economic competitiveness and sustainability of the ag sector.

One helpful service a backbone organization can provide is high-level perspective on new uses of resources, both to maximize valorization of available feedstocks and prevent negative unintended consequences that may not be visible at the project level. For example, repurposing a waste stream might generate new revenues but disrupt existing, important “virtuous cycles” such as returning certain biomass to croplands for soil health. As new uses and exchanges of wastes and by products expand, guarding against such scenarios could prevent new problems and minimize risk, both real and perceived.

Whatever pathways are chosen to align state programs to better support agriculture symbiosis innovators, industry support, involvement and leadership are essential. In fact, such leadership is a prerequisite for clusters in the ICAP Program. Efforts to foster alignment should closely coordinate with Commerce’s Industrial Symbiosis Program, where they are gaining valuable experience and insight into the kind of support agriculture innovators need, and how best to provide it. These efforts should also engage other programs that could support agriculture symbiosis projects, such as the Industrial Site Readiness Program and the Evergreen Manufacturing Growth Grants.

RECOMMENDATION #4

Forge collaboration agreements with countries and states who are symbiosis innovation leaders

Why this recommendation?

- Washington industry and policy leaders benefit from knowledge exchange and partnerships with other states and nations, as our state's collaborations with Denmark on industrial symbiosis are demonstrating.
- Such partnerships can result in the transfer of research, best practices, technologies, and policies that can improve economic and sustainability performance of Washington businesses.

This recommendation supports in the near-term a formalized Washington-Denmark agreement to collaborate on industrial symbiosis. Denmark is the world leader in symbiosis, and public and private agencies in Washington are already collaborating with symbiosis leaders in Denmark.

The tangible outcomes and benefits that collaboration agreements like this can offer to agriculture symbiosis efforts in Washington include:

- Knowledge exchange can enable Washington's industry innovators to develop better, smarter, more cost-effective symbiosis projects.
- Joint partnerships with companies elsewhere who have deep experience developing and operating symbiosis projects can result in more successful projects that achieve greater scale and benefits in Washington.
- Washington innovators can also derive inspiration from seeing the ingenious technologies and solutions that others are implementing which they may not have otherwise imagined.

Two examples of collaboration agreements in other areas that could be used as a template for agriculture symbiosis are Washington's agreement with Norway for maritime sustainability innovation, and an agreement with the Netherlands for tree fruit innovation. Key lessons can be gleaned from these collaborations to inform the design of Washington's symbiosis partnerships to achieve better return on investment for the state.

Divert Longview

Divert is bringing online an Integrated Diversion and Energy Facility at the Mint Farm Industrial Development Park in Longview.

PRE-SYMBIOSIS

- A large share of the region's food waste ends up at the landfill where it produces methane. Organic landfill waste is responsible for 15% of US methane emissions[1] and 10% of overall greenhouse gas emissions[2].
- Wasted food represents a waste of the various resources expended to grow, process, package and distribute that food, and includes associated greenhouse gas emissions throughout the process.

SYMBIOSIS IN ACTION

- Once Divert's Longview facility is brought online (estimated sometime in 2024), it will receive food waste from up to 650 grocery stores around the PNW, resulting in reduced organic waste from participating grocers and reduced greenhouse gas emissions from food waste.
- The company will use proprietary processing solutions to de-package and anaerobically digest incoming food waste. Anaerobic digestion generates biogas that can be used to produce carbon-negative renewable natural gas.

BENEFITS

Resulting renewable natural gas will be pumped directly into the Cascade Gas distribution pipeline, offsetting the use of fossil gas.

The facility's analytics system will leverage Divert's IoT (Internet of Things) platform using hardware, sensors, and algorithms to deliver data on the food waste stream to retailers so they can identify trends and further reduce waste at the source. "Source reduction is always the best solution and Divert is incentivized by its retail customer contracts to prevent food from ever leaving the supply chain."

A solid digestate product is also produced through AD that can be used as a soil amendment that supports and enhances composting.

Because the facility will process significant amounts of wasted food into carbon negative energy, it is projected to offset up to 23,000 metric tons of carbon dioxide per year, equivalent to taking roughly 5,000 gas-powered cars off the road every year.

Divert's retail partners will be supported to meet their waste diversion goals to comply with Washington's HB 1799 and Oregon Metro's food diversion laws. Production of RNG supports low carbon fuel standards in both states.

Prevent

We invent transformative technologies and create fresh data to maximize the freshness of food and prevent waste.

Provide

We take a people-first approach by recovering edible food and donating it to communities in need.

Power

Our proprietary process removes carbon from the food value chain by converting wasted food into renewable energy.

KEY TAKEAWAYS

Divert's rapid expansion nationwide over the past 16 years, shows demand from food retailers for this service, and that their model of processing organic waste to produce RNG makes good economic sense.

Food diversion laws and carbon credit markets are expected to further shift the landscape in favor of this model.

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[1] US EPA (2022), Basic Information about Landfill Gas

[2] World Wildlife Fund (2021): "10% of all greenhouse gas emissions come from food we throw in the bin"

Acknowledgements

The project partners would like to extend their sincere thanks to the many individuals who contributed their insights, experiences, and opinions to this report, particularly those active in agriculture symbiosis projects, who were interviewed or consulted by the team, hosted the team for on-site tours, and/or reviewed a report draft. These individuals include:

Virginia Emery, Beta Hatch
Karen Warner, BEAM Circular
Embrey Bronstad, Brown & Caldwell
Alan Johnston, City of Gresham
Steve Worley, City of Pasco
Michael Henao, City of Pasco
Dena Ybarra, Columbia Basin Nursery
Fabian Bühler, Danish Energy Agency
Chris Thomas, Divert Longview
Derek Allred, Double Diamond
Megan Couture, Errant Cellars Winery
Craig Smith, Food Northwest
Paul Simpson, Gross-Wen
Martin Gross, Gross-Wen
Mark Buehrer, Heart Foods
Michael Smith, Chomp (FKA Impact Bioenergy)
Doug Krapas, Inland Empire Paper Co.
Per Moller, Kalundborg Symbiosis
Trudy Slagle, Lamb Weston
Rich Burres, Lamb Weston
Roy Nott, LD Nott Company
Dale Silha, McKinstry
Mike Porter, McKinstry
Lauren Breynaert, Myno Carbon
Lauren McCloy, NW Energy Coalition
Russ Davis, Organix
Harrison Pettit, Pacific Ag
Melanie Roberts, PNNL
Peter Valdez, PNNL
Mike Werner, Qualterra
Austin Allred, Royal Dairy
Kevin Scribner, Salmon Safe
Lynn Mueller, SHARC Energy
Alicia Krueger, Sustainable Energy Ventures
Walker Dimmig, Sustainable Energy Ventures
Julia Terlinchamp, WA Dept. of Agriculture
Derek Sandison, WA Dept. of Agriculture
Megan Finkenbinder, WA Dept. of Agriculture
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Madi Roy, WA Dept. of Agriculture
Rob Duff, WA Dept. of Commerce
Aaron Peterson, WA Dept. of Commerce
Kirk Esmond, WA Dept. of Commerce
Evan Sheffels, WA Dept. of Agriculture
Jason Spadaro, WA Forest Protection Association
Darin Cramer, WA Forest Protection Association
Jim Jensen, WSU
David Gang, WSU
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Appendix A-1

Quantitative Assessment of the Washington Agricultural Industry

1. Introduction

The successful integration of symbiosis concepts into Washington's agricultural industry is dependent on the adoption of a system-level approach that maximizes the value of the industry's three most basic resources: organic material, water, and energy. One challenge to symbiosis is identifying and communicating the opportunities for collaboratively optimizing these common resources to a multidisciplinary group of ag and non-ag stakeholders that each use their own vocabulary and operate from their own perspective. For instance, industry specific terms, like "bins of apples", "bushels of grain", and "cases of wine" are all unfamiliar measurements of volume to most people outside of a handful of industry specialists among whom these are everyday terms. Additionally, definitions of basic terms, like "large-scale" and "small-scale", can be vastly different based on context. The largest winery in Washington has the capacity to crush approximately 50,000 tons of grapes per year, while the smallest frozen French fry manufacturer far exceeds that amount with an annual capacity of more than 200,000 tons of raw potatoes per year.

The quantitative assessment, which serves as a complement to the interviews and analysis also conducted for this report, is designed to provide a broad perspective of the agricultural industry to a general audience. Instead of working directly with stakeholders to highlight individual projects, this methodology focused on identifying opportunities through sector-wide inventories and geospatial analysis to discern general solutions. By evaluating generalized solutions, we can emphasize symbiosis pathways with the largest overall potential for economic and environmental impacts.

2. Methods

Throughout the quantitative analysis, we placed an emphasis on attaining data from publicly available resources. This decision is meant to help facilitate future work, as the data presented is constantly changing along with the agricultural industry.

2.1 Facility Database

The agricultural industry is dependent on a complex network of facilities that link farms to retailers. One major undertaking of this project was to aggregate a database of facilities that either store or process agricultural goods from the sources listed in table A-1.1. For each facility, several types of key information was recorded including: coordinates, address, input materials, output materials, and operating status. When available, additional information about capacity, ownership arrangements, and waste management plans were also included in the database. Although the database has more than 800 facilities documented in it at the conclusion of this project, we acknowledge that not every supply chain participant has been included.

Information about several types of facilities is available through specialized databases, but information about many of the processors that may pose the best opportunities for symbiosis were collected using the Washington Department of Ecology's Water Quality Permitting and Reporting Information System (PARIS) [2]. Within this database, common types of facilities like wineries, confined animal feeding operations (CAFOs), and fruit packers are regulated using sector-specific general permits that simplify the permitting process by using a standard format.

For other processors, we used data collected by the WSU Energy Program as a starting point [1]. We supplemented that data using two types of permit documents from the PARIS database. Permit "fact sheets" contain useful information about the history, industrial processes, and waste management plans for facilities. Often, the fact sheet contains all the information necessary for the ag processor database, but in some cases, permit applications can be an additional source of information, particularly about the amounts and types of material input and output in a typical year.

Table A-1.1: Sources used to construct the facility database

Facility Type	Source	Detailed Source	Collection Notes
Food Processors	WSU Energy Program [1]		
Agricultural Product Processors	Washington Department of Ecology, Water Quality Permitting and Reporting Information System (PARIS) [2]	See Below	
Agricultural Product Processors	City Water permits		
Fruit Packers	Washington Department of Ecology, Water Quality Permitting and Reporting Information System (PARIS) [2], [3]	Included all active facilities with fruit packer general permits	Permit applications contain data about fruit types and capacity
Confined Animal Feeding Operations	Washington Department of Ecology, Water Quality Permitting and Reporting Information System (PARIS) [2], [4]	Included all active facilities with CAFO general permits	Manure Pollution Prevention Plans (or MPPs) contain relevant information
Ag Waste Digesters	United State Environmental Protection Agency AgStar Database [5]		
Wineries	Washington Department of Ecology, Water Quality Permitting and Reporting Information System (PARIS) [2], [6]	Included all active facilities with winery general permits	Information about crush and wine capacity is included notice of intents (NOIs)
Wineries	Liquor and Cannabis Board [7]		
Milk Processors	United States Department of Agriculture, Agricultural Marketing Service (AMS) [8]	Dairy Plants Surveyed and Approved for USDA Grading Service	
Milk Handlers	United States Department of Agriculture, Agricultural Marketing Service (AMS) [9]	Regulated Pool Distributing & Supply Plants	
Public Refrigerated Warehouses	Homeland Infrastructure Foundation-Level Data (HIFLD) [10]	Public Refrigerated Warehouses	
Public Companies	10-K reports filed to US Securities and Exchange Commission (SEC) [11]		Can help identify ownership changes and changes over time

2.2 Areas of Interest

Agricultural Industrial symbiosis is a big concept. And even with advanced analytical tools, we found it impractical to characterize every potential application at an adequate level of detail. Instead, we determined the approach that would result in the most valuable information should begin with a series of high-level inventory assessments that could be used to identify areas of interest that would receive more detailed analyses. The high-level assessments were focused on the following criteria:

- **Monetary value and employment**: Characterizing the various segments of the agricultural industry based on the money they generate and number of people they employ is likely the first approach that is taken by people unfamiliar with the industry. So, it is useful to frame the industry using this basic approach before exploring alternatives that better illustrate opportunities for symbiosis.
- **Processing volume and processing hubs**: Ag supply chains often consist of multiple stages that include harvest, storage, shipping, and processing. Of these stages, symbiosis is most likely to occur at processors because they aggregate large amounts of biomass and use energy-intensive methods to convert raw goods into value-added products.
- **Change Over Time**: Segments of the ag industry that have changed the most in recent years are more likely to result in waste, as they are less likely to fit within the handful of well-established cooperative elements that took years to develop and mature within the existing industry.
- **Large number of similar facilities**: Some industries that are dependent on many smaller-scale facilities have waste problems because waste utilization often requires large economies of scale to be feasible. Community-level symbiosis projects could collectively result in the scale needed to support these types of facilities.

3. Results

3.1 Monetary Value

One of the focuses of the quantitative assessment is to identify opportunities to improve the economic performance of the agricultural industry. Minor improvements to the most valuable segments of the industry could result in significant overall improvements. Figure A-1.1 shows the value of agricultural commodities marketed from farms in 2021 [12]. The chart shows that almost 60% of the total value was concentrated among the 5 most valuable products: apples, cattle, milk, wheat, and potatoes. But 10 distinct product types (not hay or other) were valued at more than 100 million dollars in revenue, demonstrating that a diverse range of products are generated by the industry. It is also significant that the five highest value products are spread among several sub-categories, as fruits, grains, vegetables, and livestock are all represented.

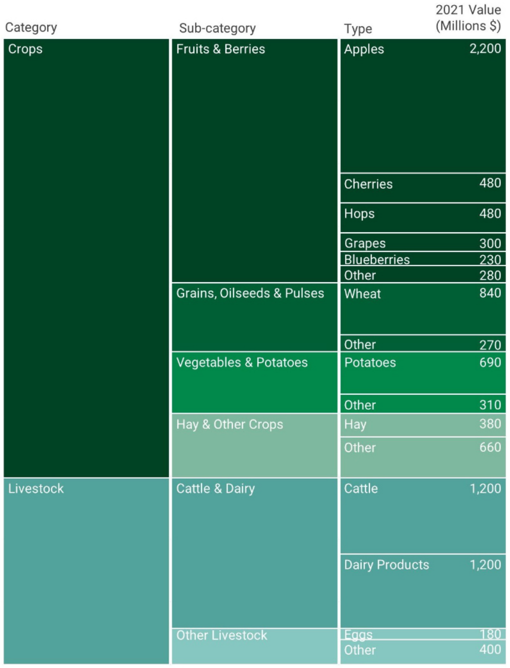

Figure A-1.1: 2021 value of agricultural commodities from Washington

The value of the agricultural industry also varies geographically. As shown in Figure A-1.2 [13], most value is generated in Eastern Washington, especially in the Yakima Valley and the Columbia Basin. The Yakima Valley, which includes Yakima, Kittitas, and Benton Counties, is an important contributor to the fruit, vegetable, and livestock sectors, as the counties combined hold 41% of total apple acreage, 56% of total grape acreage, 25% of potato acreage, and 41% of the state's dairy herd. The Columbia Basin, which consists of Grant, Adams, and Franklin Counties, also grows fruit but is proportionally more responsible for the state's vegetable and potato production. Combined, these counties hold 34% of total apple acreage, 21% of total grape acreage, 58% of potato acreage, and 21% of the state's dairy herd. While the difference in total value between Western and Eastern Washington is stark, Western Washington is still significant, as it generated more than $1.5 billion of agricultural products in 2017. An area in Northwest Washington, consisting of Skagit, Snohomish, and Whatcom counties, holds 27% of the state's dairy herd and 12% of the state's potatoes. Grains, Oilseeds, & Pulses (dry beans like lentils and chickpeas), were valued at more than 1 billion dollars in 2021 but are spread out across most of Eastern Washington. Along the state's Eastern border, in Whitman and Spokane counties, wheat is the most valuable commodity in dryland farming systems. Throughout the rest of Eastern Washington, it's used as rotational crop along with vegetables and potatoes [14].

Across all of Washington, only 1.7% of the state's residents were privately employed by companies that either produce agricultural products or manufacture food and beverages during the 3rd quarter of 2022 (calculated using population data [15] and employment data for NAICS classes 111, 112, 311, 312 [16]). But in some areas of Eastern Washington, the agricultural industry has a much greater impact on the local economy. As shown in Figure A-1.3, more than 10% of the populations in Yakima, Grant, and Adams counties were employed in either the agriculture or food and beverage industries. Across the state, most of these employees were involved in crop production, but this is partially due to data collection. Values are for July-September, when variable employment is at its annual peak [17]. Between July and December of 2021, employment in agriculture declined by 40% due to seasonal variations. Areas that produce products for fresh consumption, like apples, which require manual picking, versus row crops that can be harvested by machine employ more people in agriculture. When considering more-urban areas especially, it is worth noting that not all companies involved in food and beverage production are necessarily part of the state's ag industry, but instead manufacture products using goods from around the world for quick distribution and consumption in the state's largest population hub, the Puget Sound. For example, Starbucks, the state's most famous beverage manufacturer, sources most of the feedstock for its Kent coffee roasting plant from foreign countries in Asia, Central America, South America, and Brazil [18].

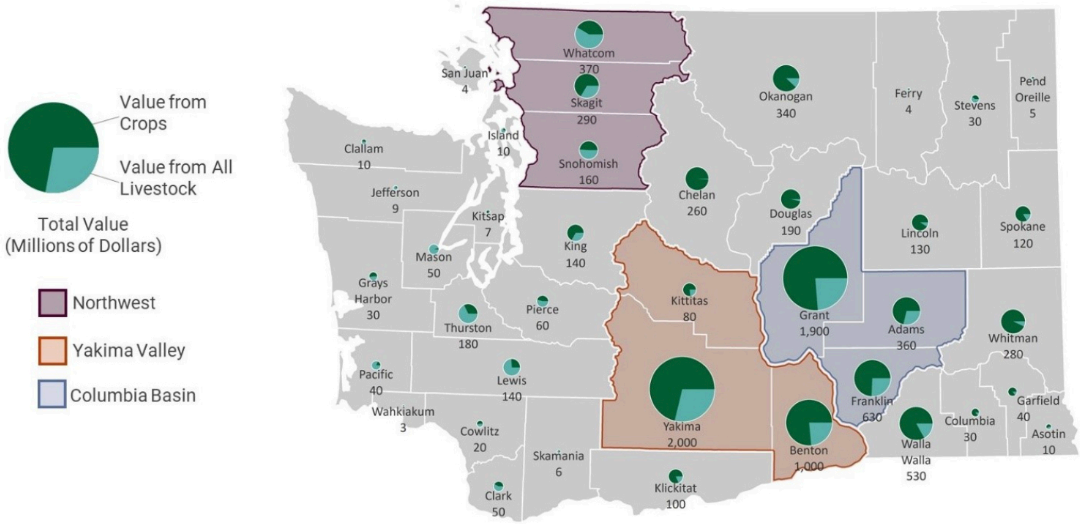

Figure A-1.2: Value of ag products by county

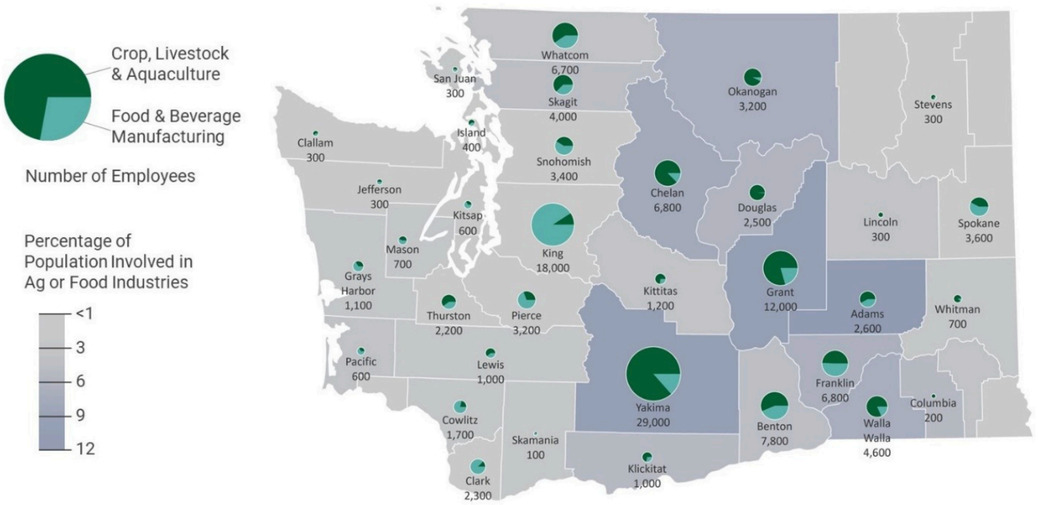

Figure A-1.3: Employment in the Washington Agricultural Industry

3.2 Processing Volume & Processing Hubs

Assessing the state's ag industry by the capacity and locations of its processors is another approach that can be taken to characterize potential for symbiosis, especially since processors typically consume large amounts of water and energy and generate a significant amount of waste biomass through trimmings and rejected product. Previous work has suggested that large industrial processors can act as "anchor" facilities that interact with small and medium-sized firms [19]. Figure A-1.3 shows the total capacity of processors (those classified in the facility database) against the total volume of crop production in 2022 [20]. By weight, more than half of all processing capacity for fruits and vegetables is used for potatoes. High-value crops like tree fruit, including apples, cherries and pears, are mostly sold for the fresh market, meaning processing makes up a small amount of their total volume. Among all fruits and berries, grapes were processed in the largest volume. Despite the overall value of grains, oilseeds, and pulses in Washington, a relatively small amount is processed, limiting applications for symbiosis.

Applications of symbiosis likely have the potential to make the greatest impact at facilities with large processing capacities. For the purposes of this study, "large" is classified as having an annual input of at least 50,000 tons per year. This method does not account for maximum daily throughput, which may be a more useful metric to classify facilities that process crops for a short period during harvest, like wineries and frozen vegetable manufacturers. Nor does this method account for the portion of waste generated from processing. Figure A-1.4 shows the locations of the state's 37 large processors that were identified in the facility database. Of these, 33 are in Eastern Washington while only 4 are in Western Washington. The 19 plants that primarily process vegetables are concentrated in the Columbia Basin, while the 9 plants that process fruit are primarily in the Yakima Valley. 3 of the state's 5 total dairy processors are in Western Washington.

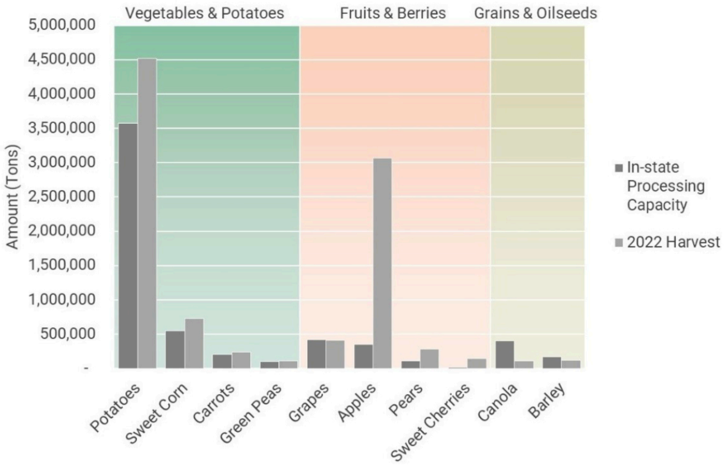

Figure A-1.4: Total production of ag products from 2021 and processing capacity from the facility database

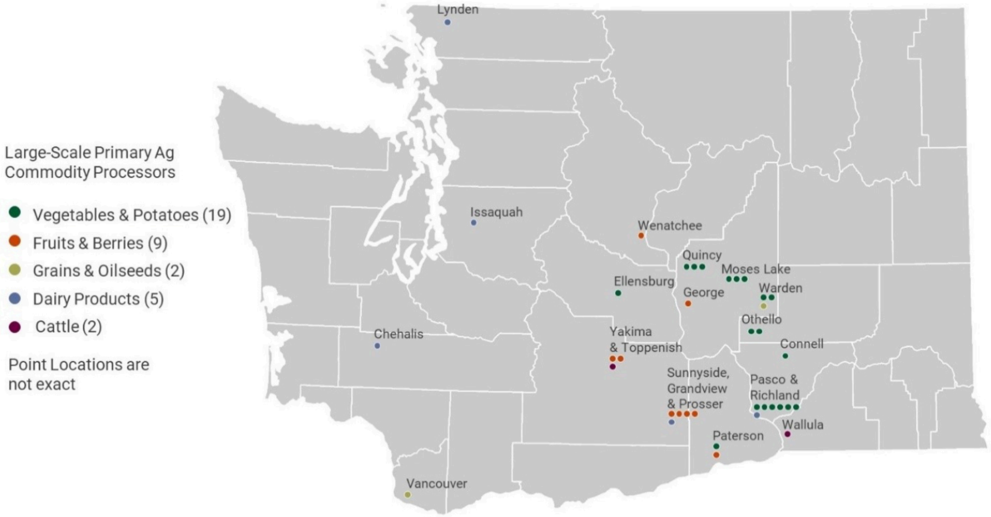

Figure A-1.5: Large ag processors in Washington by processing type, (greater than 50,000 tons per year input)

3.3 Change Over Time

Modern agriculture has been developed through the accumulation of decades of advancements in mechanization, fertilizers, and information technology [21]. This has resulted in a massive shift to the structure of the industry, as the subsistence-level family-operated farms that once dominated the industry have slowly been consolidated into larger operations. During this shift, the composition of farms also changed. Previously a single farm may have included a small orchard, several livestock, and a few fields for hay or row crops. But modern farms tend to optimize their operations for the production of fewer goods. Figure A-1.5, which was constructed from several USDA Census of Agriculture tables [22]–[29], shows the percentage of farms involved in major sectors has dropped as farms have become more specialized over time.

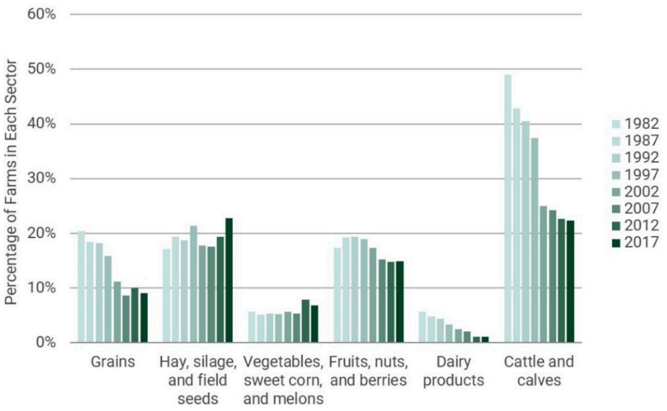

Figure A-1.6: percentage of farms involved in agricultural sub-sectors between 1982-2017

These changes have led to a necessary increase in total output, but they have also created challenges that were not a concern in the past. Because of specialization, managing waste has become more difficult for many farmers. For instance, crop wastes that were once used to feed on-farm livestock are often landfilled and manure that was used to fertilize adjacent fields is frequently just a nuisance [30].

While the number of farms involved in most sectors has changed significantly over time, the locations of their production has not changed nearly as much. Figure A-1.6 shows the centroids of ag production for several representative commodities between 1987 and 2017 [31]–[38]. The centroids of production for apples, cattle, potatoes, and wheat remained stable while dairy shifted from west to east of the Cascade Mountains. The most recent impact of this shift is a new facility that will be opened by Darigold in 2024 [39].

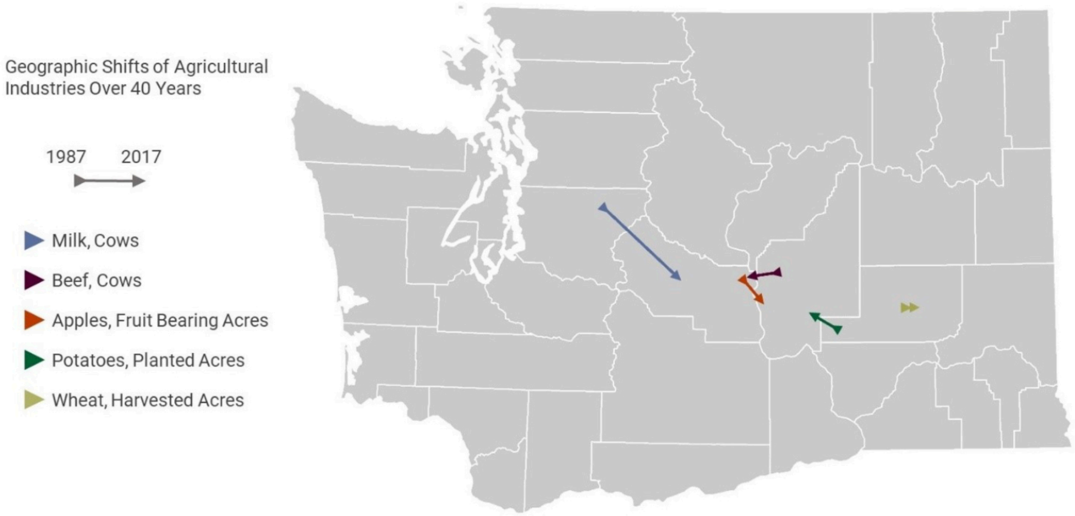

Figure A-1.7: Geographic shifts of major sub sectors over time

3.4 Many Facilities

Sectors of the ag industry that have many of the same type of facility present vastly different opportunities for symbiosis than large processors. While groups of smaller facilities don't necessarily present the best opportunity on their own, symbiosis applications that work at one location are likely to work at another, which in turn could have a significant impact. Additionally, many of these types of facilities are near each other, meaning that facilities that don't have the volume of waste to efficiently manage on their own could work with their similar neighbors to create better solutions. A long tradition of cooperatives, which support farmers in many ways [40], already exists among fruit packers, dairies, and grain elevators. Darigold and Tree Top both operate multiple large processors and are owned by cooperatives [41], [42]. These existing relationships may be useful to leverage symbiosis projects [43].

Table A-1.2: Number of Facilities by Type

Type	Number
Wineries	1,058 [7]
Dairies	284 [44]
Grain Elevators	242 [45]
Fruit Packers	181
Food Processors with Water Permits	217
Large Food Processors (shown in Figure 3)	37
Other Food Processors	415

4. Discussion

The multiple methods used to evaluate the agricultural industry failed to reveal that there is one clear-cut opportunity to implement symbiosis. Instead, it was shown that opportunities can be found in multiple sub-sectors in various parts of the state. In particular, the total value, geographic concentration, and processing capacity of fruit and berry, vegetable and potato, and livestock industries in the Yakima Valley and Columbia Basin suggests that efforts in these areas are likely to make the greatest contribution to the state's agricultural industry.

4.1 Linking Findings to Stakeholder Interviews

The results of the quantitative approach can be better understood by comparing and contrasting them with the list of existing and developing symbiosis projects presented in section **IV. Agriculture Symbiosis: Examples in Washington & Beyond**. The industry that stood out using either approach was the dairy industry. 5 anaerobic digesters projects that use primarily dairy manure were included in the list. And Royal Dairy's worm bed project also uses manure. Another area that was positively represented by either approach were the Agricultural processors in Richland and Pasco. The quantitative approach found that this area has more large agricultural processors than anywhere else in Washington, and especially projects like the

Pasco Process Water Reuse Facility could benefit a significant portion of the state's total dairy, potato, and vegetable processing capacity.

A major difference between the projects highlight how symbiosis is feasible in a broad variety of applications. The quantitative approach's results suggest that most opportunities for symbiosis lie east of the Cascade Mountains, while the list of current projects suggest that agricultural industrial symbiosis is feasible west of the Cascades, but typically at a smaller scale. Together, these approaches give a more-holistic capacity for adoption of symbiotic concepts in Washington.

4.2 Additional Work: Supply Chain Descriptions

To better understand how symbiosis can be implemented within the agricultural industry, we decided to conduct supply chain studies of the sub sectors we felt best represented the opportunities highlighted by the quantitative analysis. These include apples (expanded to include tree fruit), potatoes, and grapes. The purpose of the studies was to understand the industry on a more detailed level to help further identify potential synergies. Each study includes:

- Types of facilities that handle material in the supply chain
- Long-term trajectory of the industry in Washington
- Locations and capacities of farms, warehouses, and processors
- Seasonal variations in production
- Current uses for wastes including organic material, water, and energy

4.3 Additional Work: Energy-Related Symbiosis Assessment

As mentioned previously, one of the challenges of analyzing opportunities for agricultural industrial symbiosis is that a common tendency is to view agriculture as a series of loosely related but separate industries, instead of a complex and tightly-knit system. An example of this systems-level approach was demonstrated using two appendices that evaluated how an array of stakeholders have the potential to influence the agricultural industry's demand for fossil-based energy by 1) generating energy from waste organic sources and 2) reducing energy demand by using heat sharing.

- **Biomass-to-Energy**: Appendix B includes and evaluation of potential to use anaerobic digestion to create methane and natural gas from organic wastes like manure, fruit waste, potato waste, and wheat straw.
- **Agricultural Processor Heat Sharing**: Appendix A-2 provides and analysis of processors from several industries that use heat to dehydrate or cook raw materials. The study characterizes that heat and considers opportunities to use the waste heat for other applications.

References

[1] "Promoting Renewable Natural Gas in Washington State," 2018.

[2] "Water Quality Permitting and Reporting Information System (PARIS)," Washington Department of Ecology. https://apps.ecology.wa.gov/paris/PermitLookup.aspx (accessed Feb. 15, 2023).

[3] "Fact Sheet for Fresh Fruit Packing Draft General Permit," 2021. [Online]. Available: https://wq.ecology.commentinput.com/?id=mBGE7

[4] "Fact Sheet for The Concentrated Animal Feeding Operation National Pollutant Discharge Elimination System and State Waste Discharge General Permit And Concentrated Animal Feeding Operation State Waste Discharge General Permit," 2016.

[5] "Livestock Anaerobic Digester Database," Environmental Protection Agency, 2022. https://www.epa.gov/agstar/livestock-anaerobic-digester-database (accessed May 21, 2023).

[6] "Winery General Permit," 2018.

[7] "Licensee List," Washington State Liquor and Cannabis Board, 2023. https://lcb.wa.gov/taxreporting/licensee-list (accessed May 21, 2023).

[8] "Dairy Plants Surveyed and Approved for USDA Grading Service," United States Department of Agriculture, Agricultural Marketing Service. https://apps.ams.usda.gov/dairy/ApprovedPlantList/ (accessed May 04, 2023).

[9] "Regulated Pool Plants," 2023.

[10] United States Department of Homeland Security, "Homeland Infrastructure Foundation-Level Data (HIFLD)." https://hifld-geoplatform.opendata.arcgis.com/ (accessed Apr. 09, 2021).

[11] D. C. Washington, "United States Securities and Exchange Commission Form 10-k Annual Report Pursuant to Section 13 Or 15(d) of the Securities Exchange Act Of 1934 General Instructions."

[12] "Farm Income and Wealth Statistics," United States Department of Agriculture, Economic Research Service, 2023. https://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics.aspx (accessed May 21, 2023).

[13] "2017 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 2. Market Value of Agricultural Products Sold Including Food Marketing Practices and Value-Added Products: 2017 and 2012," 2017. Accessed: May 21, 2023. [Online]. Available: https://www.nass.usda.gov/Quick_Stats/Ag_Overview/stateOverview.php?state=WASHINGTON

[14] M. J. Porter, "Nitrogen Management of Winter Canola in the Inland Pacific Northwest," 2019.

[15] "County Population Totals and Components of Change: 2020-2022," United States Census Bureau, 2023. https://www.census.gov/data/tables/time-series/demo/popest/2020s-counties-total.html (accessed Jun. 05, 2023).

[16] "Quarterly Census of Employment and Wages: Employment and Wages Data Viewer," United States Bureau of Labor Statistics, 2023. https://data.bls.gov/cew/apps/data_views/data_views.htm#tab=Tables (accessed Jun. 05, 2023).

[17] "Agricultural employment and wages," Washington State Employment Department, 2022. https://esd.wa.gov/labormarketinfo/agricultural employment-and-wages (accessed Jun. 05, 2023).

[18] J. A. Cooke, "From bean to cup: How Starbucks transformed its supply chain," Supply Chain Quarterly, 2015. https://www.supplychainquarterly.com/articles/438-from-bean-to-cup-how-starbucks-transformed-its-supply-chain (accessed Jun. 06, 2023).

[19] B. Notarnicola, G. Tassielli, and P. A. Renzulli, "Industrial symbiosis in the Taranto industrial district: Current level, constraints and potential new synergies," J Clean Prod, vol. 122, pp. 133–143, May 2016, doi: 10.1016/j.jclepro.2016.02.056.

[20] "Washington State Ag Overview," United States Department of Agriculture, National Agricultural Statistics Service, 2022.

[21] C. Dimitri, A. Effland, N. Conklin, and U. States, "The 20th Century Transformation of U.S. Agriculture and Farm Policy," 2005. [Online]. Available: www.ers.usda.gov

[22] "1982 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 49. Summary by Size of Farm: 1982," 1982.

[23] "1987 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 51. Summary by Size of Farm: 1987," 1987.

[24] "1992 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 49. Summary by Size of Farm: 1992," 1992.

[25] "1997 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 49. Summary by Size of Farm: 1997," 1997.

[26] "2002 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 55. Summary by Size of Farm: 2002," 2002.

[27] "2007 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 58. Summary by Size of Farm: 2007," 2007.

[28] "2012 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 64. Summary by Size of Farm: 2012," 2012.

[29] W. 77, "2017 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 71. Summary by Size of Farm: 2017," 2017.

[30] M. P. Bernal, "Grand Challenges in Waste Management in Agroecosystems," Front Sustain Food Syst, vol. 1, Sep. 2017, doi: 10.3389/fsufs.2017.00001.

[31] "1987 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 11. Cattle and Calves-Inventory and Sales: 1987 and 1982," 1987.

[32] "1987 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 24. Grains-Corn, Sorghum, Wheat, and Other Small Grains: 1987 and 1982," 1987.

[33] "1987 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 28. Fruits and Nuts: 1987 and 1982," 1987.

[34] "1992 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 27. Cotton, Tobacco, Soybeans, Dry Beans and Peas, Potatoes, Sugar Crops, and Peanuts: 1992 and 1987," 1992.

[35] "2017 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 11. Cattle and Calves -Inventory and Sales: 2017 and 2012," 2017.

[36] "2017 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 24. Selected Crops Harvested: 2017," 2017.

[37] "2017 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 31. Fruits and Nuts: 2017 and 2012," 2017.

[38] "2017 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 29. Vegetables, Potatoes, and Melons Harvested for Sale: 2017 and 2012," 2017.

[39] "Darigold Breaks Ground on New Production Facility in Pasco, Wash.," PRN Newswire, 2022. https://www.prnewswire.com/news-releases/darigold-breaks-ground-on-new-production-facility-in-pasco-wash-301620667.html (accessed May 21, 2023).

[40] C. Ling, "What Cooperatives Are (and Aren't)," 2009.

[41] "Our History: A Timeline of the Northwest Dairy Association and Darigold," Darigold. Our History A Timeline of the Northwest Dairy Association and Darigold (accessed May 21, 2023).

[42] "About Tree Top," Tree Top. https://www.treetop.com/about/ (accessed May 21, 2023).

[43] L. W. Baas and F. A. Boons, "An industrial ecology project in practice: Exploring the boundaries of decision-making levels in regional industrial systems," J Clean Prod, vol. 12, no. 8–10, pp. 1073–1085, Oct. 2004, doi: 10.1016/j.jclepro.2004.02.005.

[44] "WA Dairies," Washington Geospatial Open Portal, 2022.

[45] M. Jaller, "Grain Transportation Study Final Report Water Foundation," 2022.

Appendix A-2

Detailed Supply Chain Summary and Waste Assessment

1. Approach

The detailed supply chain reviews focus on characterizing some of Washington's most intriguing ag goods. These include apples, Washington's most valuable crop; potatoes, the crop processed in the largest quantity; and grapes, a crop that has experienced rapid growth for processing and cultivation in the recent past. Focus is placed on biomass, energy, and water along each of these supply chains with the goal of identifying opportunities to implement symbiosis as well as the likely barriers that would limit its adoption. The Following were questions we used to describe each supply chain:

Flow of Material between farms, storage, and processors

- How are crops used, are they sold fresh or processed?
- What types of facilities are used in the supply chain?
- What is the balance between quantity and quality in determining crop value?

Farm level trends

- Where are crops grown?
- How large are individual farms?
- How have farms changed in the recent past?

Storage

- Is storage on-farm, owned by cooperatives, or at processors?
- Does storage result in waste biomass, water or energy?
- When are crops available throughout the year?

Processing

- How much waste, residual biomass, water, and energy are generated?
- Is the waste sold to other markets already?
- How does scale impact operations?

Symbiosis Examples

- Are there existing examples of symbiosis within the supply chain?

2. Key Findings

Each supply chain is significantly different, so studying three supply chains with one methodology provided useful insights into opportunities to implement agricultural-industrial symbiosis. The list below describes key observations:

- Seasonality is an important consideration for all elements of supply chains. Some crops, like potatoes, can be stored and processed throughout the year, while others, like grapes, have a short processing season.
- The number and scale of processors is variable across industries. There are hundreds of wineries in Washington, while there are just a handful of tree fruit and potato processors. Depending on the approach being used for symbiosis, either type of facility may be preferable.
- Efficiency is an emphasis for most companies already. High value food waste is typically sold as cattle feed and wastewater is often used for irrigation. Exceptions to this observation are typically at storage facilities and smaller processors.
- The location of supply chain elements is also an important consideration. Tree Fruit processors are all in cities in the Yakima Valley, and are often located near other industrial facilities. Some wine and potato processors are in cities, like Pasco, Richland, and Quincy, which have other types of industry nearby, while others are relatively isolated from potential symbiosis partners.

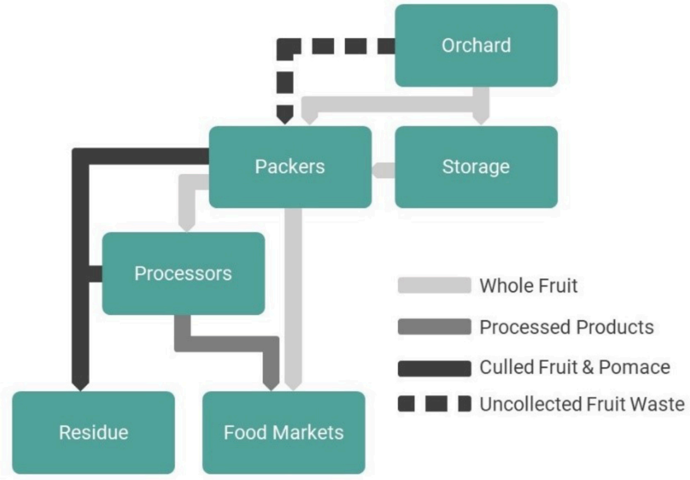

Figure A-2.1: General tree fruit supply chain

3. Tree Fruit Supply Chain

3.1 Supply Chain Overview

The supply chain for tree fruit is a multi-stepped process that results in both fresh fruit and processed foods that are available to consumers throughout the year. As shown in Figure A-2.1, the supply chain begins at the orchard. Following harvest, fruit is delivered to warehouses that store and pack fruit. The roles of individual warehouses can vary as some packing houses also have fruit storage capacity, with the ability to store some or all of the fruit they pack in a year. The supply chain also varies depending on the type of fruit. Pome fruit, which include apples and pears, can be stored for several months after harvest in a controlled atmosphere environment. Cherries, which are a type of stone fruit, begin to spoil quickly after harvest, and are rushed directly to packing houses.

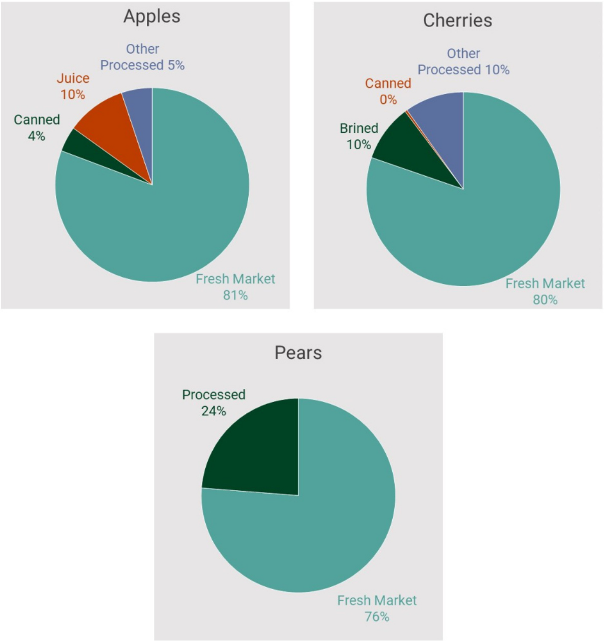

Figure A-2.2: Usage rates for tree fruit grown in Washington, 2016

One of the key functions of packing houses is fruit sorting, which determines whether fruit is suitable for the fresh market or processing. As shown in figure A-2.2, depending on the species, between 81 and 76 percent of fruit is sold fresh [1]. In this context, the term "fresh" refers to any whole, unprocessed fruit, regardless of the length of the time the fruit has been held in storage. The storage lifespan of pome fruits can vary from a few months to a year depending on the variety. Fresh market fruit is sold to a wide variety of clients, with most fruit going to either export or domestic wholesale for uses in restaurants and sales in grocery stores [2]. Some lower quality fruit is suitable for processors. Several in-state companies make an array of products including juice, sauce, dehydrated fruit, fruit essence, and fresh-sliced packaged fruit.

3.1 Orchard trends

As shown in figure 3, the tree fruit industry is mostly limited to a strip of Washington that runs north and south along the east side of the Cascade Mountains [3]. The USDA has divided this region into three areas: the Yakima Valley which includes Benton, Kittitas and Yakima Counties; the Columbia Basin which includes Adams, Franklin and Grant counties; and Wenatchee which includes Chelan, Douglas, and Okanogan counties [4]. Apples have always been the dominant tree fruit in Washington and comprised 74% of the total tree fruit acreage during the last Census of Agriculture in 2017 [5]. Sweet cherries came second with 17% and pears third with 9%. Small amounts of other stone fruit like apricots, nectarines, plums, sour cherries, and peaches are also grown in Washington. The Yakima Valley contained 38% of total tree fruit acreage in the state, the Columbia Basin 32% and Wenatchee 23%. Most of the remaining 7% of acreage was in Klickitat and Walla Walla counties.

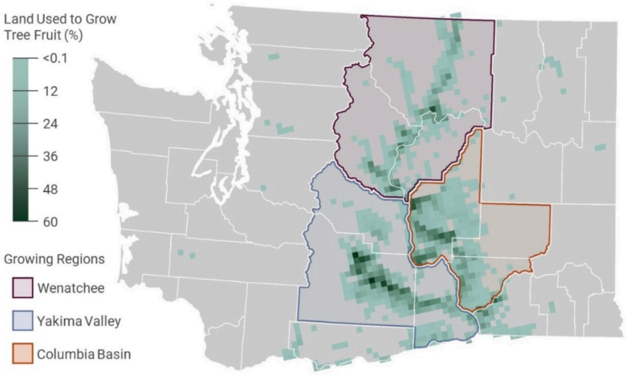

Figure A-2.3: The tree fruit growing region in Washington

As shown in figure A-2.3, the tree fruit industry is mostly limited to a strip of Washington that runs north and south along the east side of the Cascade Mountains [3]. The USDA has divided this region into three areas: the Yakima Valley which includes Benton, Kittitas and Yakima Counties; the Columbia Basin which includes Adams, Franklin and Grant counties; and Wenatchee which includes Chelan, Douglas, and Okanogan counties [4]. Apples have always been the dominant tree fruit in Washington and comprised 74% of the total tree fruit acreage during the last Census of Agriculture in 2017 [5]. Sweet cherries came second with 17% and pears third with 9%. Small amounts of other stone fruit like apricots, nectarines, plums, sour cherries, and peaches are also grown in Washington. The Yakima Valley contained 38% of total tree fruit acreage in the state, the Columbia Basin 32% and Wenatchee 23%. Most of the remaining 7% of acreage was in Klickitat and Walla Walla counties.

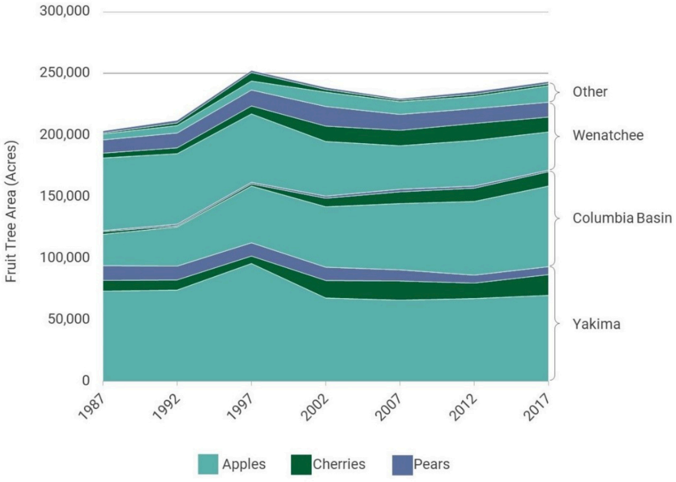

Figure A-2.4: Tree Fruit Acreage in Washington

Figure A-2.4 uses data from 7 consecutive agriculture censes [5]–[10] to show trends in overall acreage. Across the state, total acreage increased 19% between 1987 and 2017 from 203,000 to 243,000 acres. Cherry acreage almost tripled with a 173% increase, apple acreage increased 10% and pear acreage fell 17%.

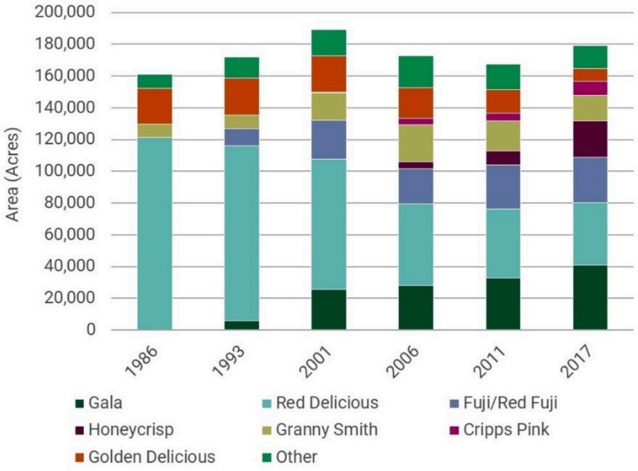

Figure A-2.5: Washington Apple Varieties

In 1997, total apple acreage peaked, in what would be a temporary bubble, as farmers were faced with reduced demand for red delicious apples. As shown in Figure A-2.5, this bubble was followed by a large number of orchards being replaced with new varieties [4]. As of 2017, 69% of apple acreage in Washington had been planted since 1996. Other orchards either went out of business or changed fruit species altogether [2], so that only 27% of apple trees in production in 1996 were still in production in 2017.

The decline in pear acreage has mostly been due to a halving of acreage in the Yakima Valley. But this trend was not consistent throughout the state. In 2017, Wenatchee contained 57% of the state’s pears after an increase in acreage of 12% over the past 30 years.

The Columbia Basin experienced an overall 173% increase in acreage between 1987 and 2017.

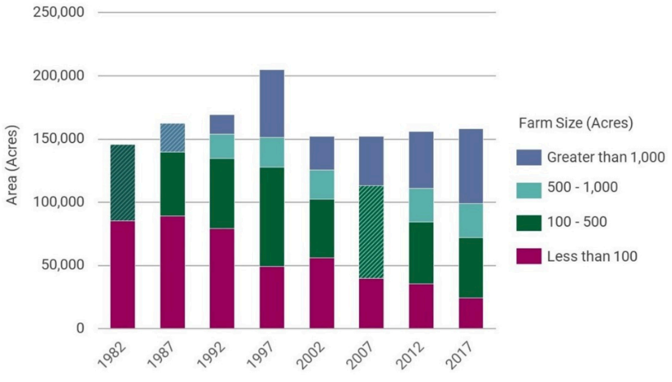

Figure A-2.6: Orchard Acreage held by Farm Size

Unlike the Yakima and Wenatchee areas, it was not subject to the “apple bubble” acreage decrease in the late 90’s, likely because the Columbia Basin was an area that was newer to the fruit industry at the time and had fewer established orchards with out-of-fashion varieties.

As shown in figure A-2.6 [11]–[17], another ongoing and significant trend is the consolidation of the orchard sector [2], [18]. Since 2002, total acreage has stabilized and is easier to analyze. Over the period of these censuses, an increase in orchard land held by large landholders has increased at a rate greater than 8% than the preceding census. Land held by small size operations has also consistently decreased at a rate of 4% per census.

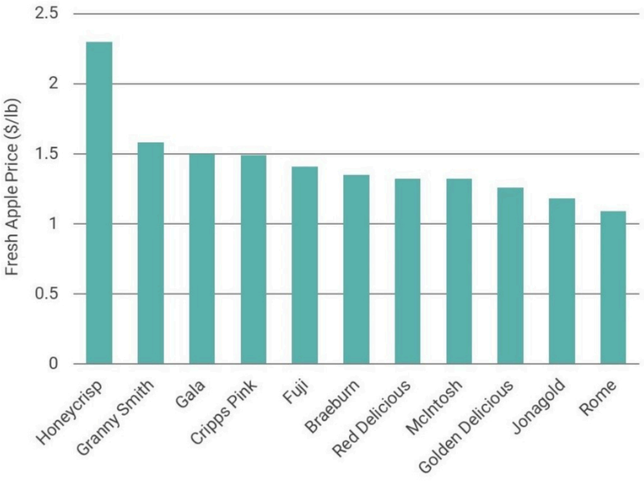

Figure A-2.7: 2022 US Apple Prices

Variety selection for fruit is based on orchard expected return, so farmers are continuously working to modernize their orchards with new varieties that offer improved flavor, appearance, easier management and hardiness. Particularly the apple industry has seen a major shift towards newer varieties. As one example, the Honeycrisp variety began to experience a rapid rise in popularity in the mid 2000’s [4] following its release by the University of Minnesota in 1992 [19]. Farmers have mostly been attracted to Honeycrisp by its industry-leading prices, as shown in Figure A-2.7, as average non-organic Honeycrisp apples sold for 40% more than the classics red delicious and golden delicious [20]. But the price of fresh market fruit is not the only metric that farmers use. Honeycrisp has one of the lowest fresh-use rates of any variety due to a relatively high rate of defects, particularly bitter pit [19], in the fruit and a relatively short storage lifes [21]. As shown in figure A-2.8, despite being the 3rd most-produced variety in 2022, more Honeycrisp apples were sent to processors than the first and second most-produced varieties. Figure A-2.8 was calculated using tables 7 & 11 in the 2022 Apple Outlook Report [20].

This means that not all farmers have determined that purchasing Honeycrisp saplings is the most economical decision, and other varieties like Gala and Fuji, which sell for less than Honeycrisp, but still have a higher value than the once dominant Red Delicious, have also seen an increase in acreage throughout the 2000s. Even as the market shares of these newer varieties continue to grow, more new varieties are also beginning to enter the market. For instance, two varieties on the rise, Cosmic Crisp and SweeTango, were both crossbred from Honeycrisp [22], [23].

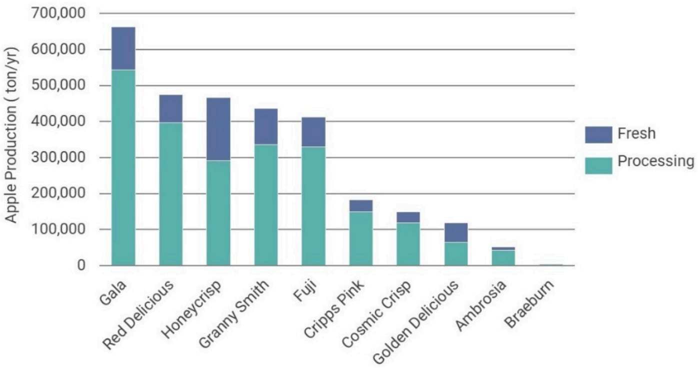

Figure A-2.8: Production and use of apple varieties, Washington, 2022 (Calculated)

Different fruit varieties are harvested at different points throughout the season, as the harvest window for each variety is typically just a couple weeks. Orchards grow multiple varieties of one type of fruit so that the harvest can be staggered over a longer period, requiring a smaller number of laborers for a longer period of time [2]. The apple harvest begins in the late summer and continues through late fall. Harvest dates are also dependent on weather, so year-to-year variations and local climates can shift harvest windows by weeks. The major varieties picked early in the season include Gala, Honeycrisp, and Golden Delicious; mid-season varieties include Red Delicious, Granny Smith, and Cosmic Crisp; and late season varieties include Fuji and Cripps Pink (Pink Lady). Pear season roughly coincides with apple season. Summer pears, which are primarily Bartlett pears, are harvested in August. Winter pears, include Anjou and Bosc pears, and are harvested in late August and September [24].

Cherry season begins several months earlier than pome fruit harvest. It runs from mid spring to late summer, depending on the variety and climate. Bing cherries are frequently used as a benchmark to compare other varieties because they account for half of the state's total acreage [25]. Harvest for Bing cherries starts in the early-to-mid season at roughly the same time as Rainier cherries; Chelan cherries are harvested one to two weeks earlier; and Lapin, Skeena, and Sweetheart cherries are harvested one to three weeks later.

3.2 Fruit Packing and Storage

As shown in figure A-2.9, there are more than 60 active fruit packing and storage companies in Washington, and the industry is disaggregated. As is shown in figure A-2.10, no company reported handling more than 7% of the state's total packing or storage capacity over the last three years. Data was collected from permits [26]. Consolidation has been a long-term trend in the packing industry, as there were 154 packing houses in 1985 [2]. Some areas have been more affected by this trend, like Brewster where several companies have consolidated and Waitsburg where the largest packer in the state handles a significant amount of fruit from Franklin and Walla Walla counties. Areas where the fruit growing industry has existed the longest, particularly Yakima and Wenatchee, have more established infrastructure, while the Columbia Basin has relatively few packing and storage facilities. Pome fruit can be stored for months after harvest. A survey of Washington fruit packers found that most storage facilities use controlled atmosphere storage, which holds fruit at specific set points for oxygen, carbon dioxide, and temperature among other variables to maximize the storage life [27], [28]. Some facilities also use a dynamically controlled atmosphere, which is more intensively managed and varies storage set points throughout the year [29]. Depending on the variety and storage technique, apples can typically be stored for 10 – 12 months. Honeycrisp is the most notable exception with its relatively short six-month storage life [21]. Most pears have a shorter storage life than apples, as Bartlett pears last approximately 6 months, Bosc last 8 months, and Anjou last 10 months.

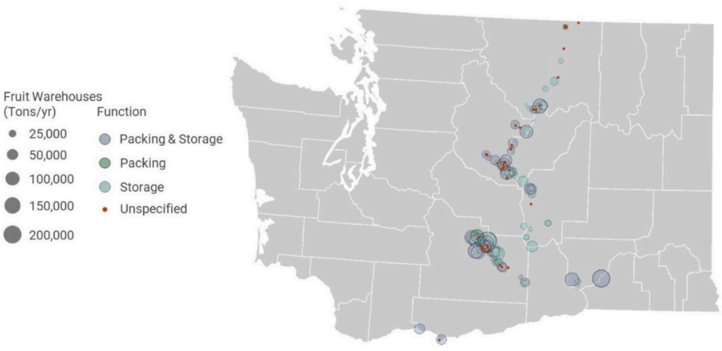

Figure A-2.9: Locations of fruit packers

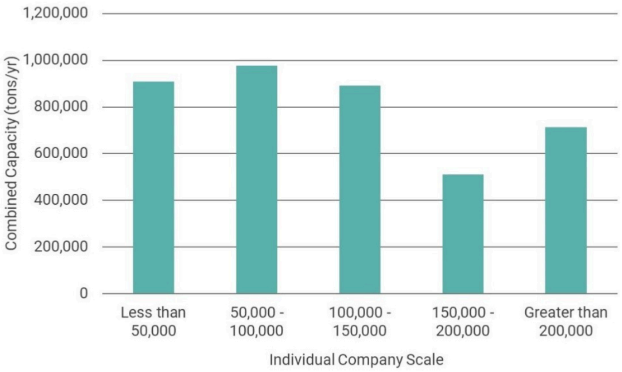

Figure A-2.10: Most fruit packers are mid-sized companies

Cherries have a much shorter storage life than pome fruit. Following harvest, packers rush to cool cherries. After picking, each hour that the internal temperature of cherries are over 40 degrees is equivalent to one less day of shelf life at stores [30]. Immediate measures to jump-start the packing process even before arrival to the packing house may be taken. Stemilt uses mobile equipment that begins the cooling process at the orchard [30]. Once cherries are cooled, they are sent to markets as soon as possible.

3.2 Fruit Processing

The distribution of fruit is dependent on grading. The highest quality fruit are sold for the fresh market, while lower quality fruit are either sold to secondary fresh markets, processors, or culled. The differences between the higher quality grades is based solely on appearance, like whether an apple has the specified amount of red color on its skin [31]. In lower quality grades, a variety of other defects that affect taste and texture may also be present. Fruit with rot is not sold for human consumption. These different grades result in a price hierarchy for apples and pears. As shown in Figure A-2.11, fresh fruit sell for significantly more than any other grade [32]. Next fresh slices, frozen, canned, dried, and juice markets offer the best prices in that order. In general, the uses that modify the fruit the least pay the most for the fruit.

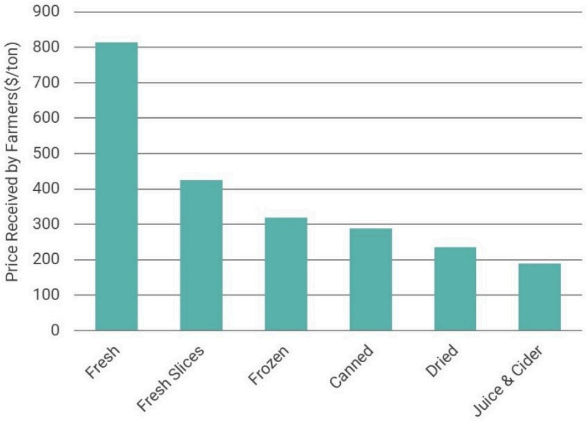

Figure A-2.11: Apple Prices by use, 2017, United States

Fruit processors are located in four areas: Wenatchee, Yakima, Prosser/Sunnyside/Grandview, and Royal City. While there are many companies that use tree fruit in their products, the focus of this work is directed towards companies that process larger quantities. Figure A-2.12 shows fruit processors in Washington. Processors were identified through the water permit database [26].

There are seven juice processors in Washington. Key processes for fruit juice canning include washing, juice extraction (crushing), steam pasteurization, and packaging. Some plants also concentrate fruit juices using steam, replacing the need to pasteurize later. The residuals from juicing consist of pomace from whole the crushed fruit. The largest apple processor is Tree Top, which primarily makes apple juice. Tree Top is a cooperative [33] owned by farmers throughout the region and has existing relationships with an adjacent winery owned by Zirkle Fruit [34].

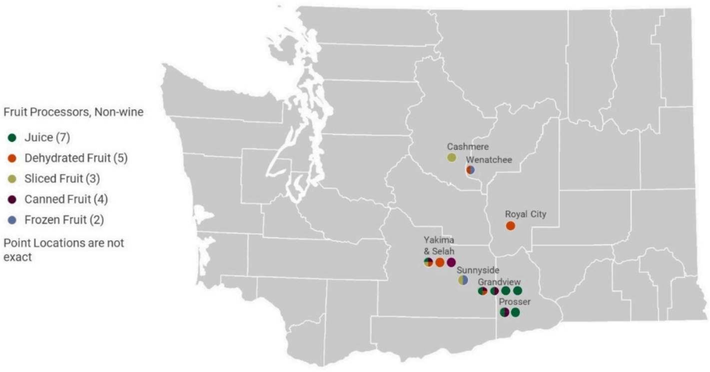

Figure A-2.12: Fruit Processors, by output type

There are four sauce processors in Washington, which are located in the Yakima Valley. Most fruit sauces consist of apples, although other fruit like grapes may be used. Key processes consist of washing, coring and peeling, slicing or crushing, filling, and heat sterilization.

Two sliced apple plants operate in Washington. Sliced fruit processing is relatively simple, as fruit is sliced, sprayed with agents to inhibit browning, and packaged.

Other fruit processing primarily serves to make intermediary ingredients for other foods like fruited breads and snacks. The processes to make these products vary from plant to plant, depending on the specifications that are demanded at different locations.

3.2 Waste Biomass Inventory

Waste biomass from the fruit industry can be generated from a variety of sources, like annual orchard thinning waste, or periodic orchard tearout when aging trees are replaced. The most valuable waste is culled fruit. At the orchard level, waste fruit can either fall on the ground prior to harvest or be rejected and dropped on the ground by fruit pickers. While this is a potentially a significant source of fruit, it is typically not collected. Especially fruit that falls on the ground can harbor pathogens, so it needs to be collected separately from regular fruit picking [35], although waste fruit can also cause issues for orchard management [36], [37]. Fruit lost in orchards can sometimes be mulched along with other waste like thinned branches and then spread over the trunks of trees to fertilize following crops [37]. At packing houses, fruit that is not deemed suitable for the fresh market are then graded for the processing market, or as a last resort, culled. The waste generated by fruit processors is dependent on partially dependent on the type of processor, but generally this waste is called pomace and consists of skins, peels, stems, seeds, and cores of fruit [38].

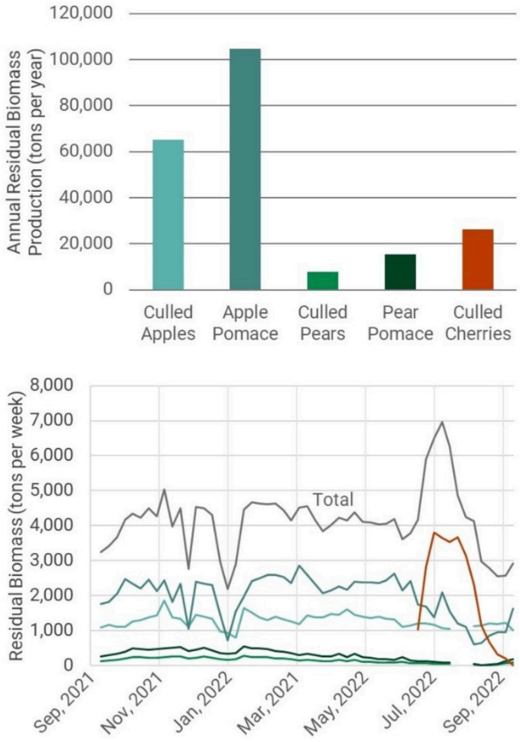

Figure A-2.13: Fruit Waste Seasonality during the 2021 season

As shown in figure A-2.13, shipments of fruit throughout the year can be used as an indicator for when waste fruit is available [39]–[41]. For pome fruit, shipments to fresh markets and processors are continuous throughout the year, but not at a constant rate. At the start of the harvest season, shipments are in a lull, which begin to ramp-up following the harvest of the first major varieties in mid-September. For the next several months, shipments occur at a steady rate, with the exception of interruptions around the major winter holidays. By late May, apple shipments begin to decline until the end of summer when the next season's apples begin to ship. The drop in shipment quantities in May is likely due to a combination of factors, as the storage lifespan of most major apple varieties begin to expire over the summer and packers are also likely trying to clear space for the cherry harvest and then the next year's apple harvest. Pear shipments begin to decrease by mid-winter as some varieties run out of stock due to the shorter storage lifespan of pears. Cherry shipments begin immediately after the start of cherry harvest and mirror the rate of harvest. Once the cherry season is over, shipment quickly comes to an end.

For pome fruit, the cull rate makes up a relatively small percent of the total fruit because there are several secondary processing markets with purchasers located throughout the growing region. No explicit information about cull rates is available, but between 2017 and 2021 3% of apples in the US were listed as unsold [20]. In Washington, the unsold rate was 4.6% over the same period [42].

Cherries have a much higher cull rate than the other fruit because there are fewer secondary markets for damaged fruit. While processed cherries make up a significant amount of the overall market, these cherries are often purpose grown with a variety that lends itself to brining [43]. Some sorted-out fruit may also be used, but many cherries are processed whole, so it should be assumed that all rejected fruit is suitable for processing. According to the WSU enterprise budget, typical cull rates are 20% and farmers should expect to receive a price for culls that is between 10% and 2.5% of fresh market cherries [44].

Pomace generation rates can be difficult to find on a company by company basis, but have been reported to vary between 9-45% in water permits. Waste is highest for products where the fruit is kept whole, or in large pieces, like sliced apples. A "general rate" of 25% is used for fruit pomace generation in Figure A-2.12 [38], [45].

3.3 Biomass Uses

Waste fruit currently has several uses. Most processors and some fruit packers sell fruit for cattle feed. As shown in Figure A-2.14, a significant amount of waste fruit from fruit packing facilities is also landfilled, representing a significant opportunity.

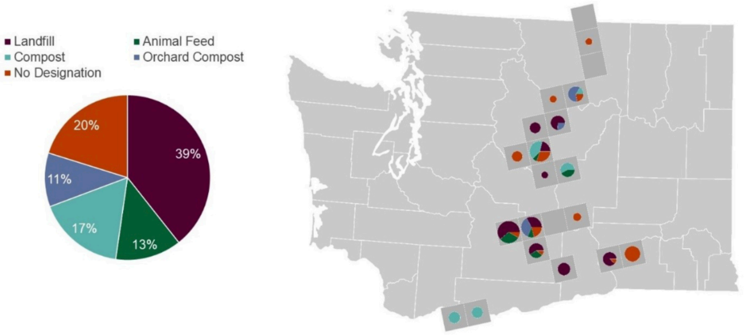

Figure A-2.14: Reported waste fruit uses by fruit packers

Residual fruit can be used as a forage replacement in animal feed for cattle and hogs [46]. It is a succulent feed, meaning animals like to eat it, and it is particularly high in fiber [47]. In diet formulations, residual fruit is fed as a forage component, working in a similar function as corn silage. Feeding rates for residual fruit can vary depending on diet formulations, but typical feeding rates for both growing cattle and milking heifers are near 18 pounds per day [47]. One potential challenge is whether or not culled cherries can be fed to cattle. The flesh of cherries is non-toxic, but the pits and leaves are poisonous [48].

Fruit waste has been widely researched as a potential component for anaerobic digestors that produce biogas. At least one study has been conducted to determine biogas potential from an apple and manure slurry [49].

Some packing companies also own orchards. One option for these companies is to recycle their own residuals by composting. For instance, Stemilt composts fruit waste, thinned branches and leaves, locally procured manure, and lime at a composting facility near their orchards [50]. This approach reduces fertilizer demand in addition to reducing fruit waste. Milne Fruit also sells waste fruit to wineries that use it to compost in their vineyards.

3.4 Water

Water is consumed at each level of the supply chain, but some water is difficult to collect, particularly irrigation water. Water from storage, packing, and processing is easier to collect and reuse. Based on estimates derived from water consumption reports from water permits, fruit storage requires approximately 0.1 gallons per ton and fruit packing requires approximately 2 gallons per ton. Water consumption is highly variable by plant. Part of the variability is due to the different products lines that each plant has, although some procedures, like washing, are universal. But the variability is also dependent on the design of the facility. Some have equipment that either uses less water or collects and recycles water [51].

The wastewater quality from fruit depends on the processes the water has been used for. Water used for cooling, or non-contact cooling water (NCCW) has higher temperatures and softening agents that can foul the water. Fruit washing water and evaporated water from juice concentration contains organics. Water used for drenching fruit before storage has pesticide chemicals [52].

3.5 Energy Consumption

Energy consumption values are not available on a plant-by-plant basis in the state of Washington, but several broad industry assessments have been conducted that identify sources that can be recycled. Fruit processors produce steam to concentrate fruit juice and sterilize containers [53]. The hot water used for refrigeration at storage facilities may also be a source of energy.

Tree Fruit References

[1] "Noncitrus Fruits and Nuts 2016 Summary," 2017.

[2] D. M. Granatstein and R. T. Schotzko, "A Brief Look at the Washington Apple Industry: Past and Present," 2004. [Online]. Available: https://www.researchgate.net/publication/251355979

[3] "CropScape," United States Department of Agriculture, National Agricultural Statistics Service, 2021.

[4] C. Mertz, D. Koong, and S. Anderson, "Washington Tree Fruit Acreage Report 2017," 2017.

[5] "2017 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 31. Fruits and Nuts: 2017 and 2012," 2017.

[6] "2012 Census of Agriculture - County Data: Washington, Table 31. Fruits and Nuts: 2012 and 2007," 2012.

[7] "2007 Census of Agriculture - County Data: Washington, Table 32. Fruits and Nuts: 2007 and 2002," 2007.

[8] "2002 Census of Agriculture - County Data: Washington, Table 31. Fruits and Nuts: 2002 and 1997," 2002.

[9] "1997 Census of Agriculture - County Data: Washington, Table 31. Fruits and Nuts: 1997 and 1992," 1997.

[10] "1987 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 28. Fruits and Nuts: 1987 and 1982," 1987.

[11] "2017 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 37. Specified Fruits and Nuts by Bearing and Nonbearing Acres: 2017 and 2012," 2017.

[12] "2012 Census of Agriculture - State Data: Washington, Table 39. Specified Fruits and Nuts by Bearing and Nonbearing Acres: 2012 and 2017," 2012.

[13] "2007 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 35. Specified Fruits and Nuts by Bearing and Nonbearing Acres: 2007 and 2002," 2007.

[14] "2002 Census of Agriculture - State Data: Washington, Table 36. Specified Fruits and Nuts by Bearing and Nonbearing Acres: 2002 and 1997," 2002.

[15] "1982 Census of Agriculture - State Data: Washington, Table 42. Specified Fruits and Nuts by Bearing and Nonbearing Acres: 1982 and 1978," 1982.

[16] "1997 Census of Agriculture - State Data: Washington, Table 49. Summary by Size of Farm :1997," 1997.

[17] "1992 Census of Agriculture - State Data: Washington, Table 42. Specified Fruits and Nuts by Acres: 1992 and 1987," 1992.

[18] L. Jarosz and J. Qazi, "The geography of Washington's world apple: global expressions in a local landscape," 2000.

[19] D. A. Rosenberger, C. B. Watkins, and L. Cheng, "Honeycrisp: Promising Profit Maker or Just Another Problem Child?," New York Fruit Quarterly, 2001. [Online]. Available: https://www.researchgate.net/publication/264879357

[20] "Industry Outlook 2022," US Apple, 2022.

[21] "Honeycrisp," Washington State University Tree Fruit. https://treefruit.wsu.edu/variety/honeycrisp/ (accessed Feb. 15, 2023).

[22] "Cosmic Crisp® WA 38." https://treefruit.wsu.edu/variety/cosmic-crisp-wa-38/ (accessed Feb. 15, 2023).

[23] "SweeTango® (Minnieska)," WSU Tree Fruit Comprehensive Tree Fruit Site. https://treefruit.wsu.edu/variety/sweetango/ (accessed Feb. 15, 2023).

[24] "Varieties," Washington State University Tree Fruit. https://treefruit.wsu.edu/varieties/ (accessed Feb. 15, 2023).

[25] A. Thompson, M. Whiting, and L. Long, "Sweet Cherry Cultivars for the Fresh Market," 2021. Accessed: Feb. 15, 2023. [Online]. Available: https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw604.pdf

[26] " Water Quality Permitting and Reporting Information System (PARIS)," Washington Department of Ecology. https://apps.ecology.wa.gov/paris/PermitLookup.aspx (accessed Feb. 15, 2023).

[27] R. Blakely, "Washington Apple Storage Survey Results 2017." Accessed: Dec. 07, 2022. [Online]. Available: http://treefruit.wsu.edu/article/washington-apple-storage-survey-results-2017/

[28] J. Graziano and M. Farcuh, "Controlled Atmosphere Storage of Apples," University of Maryland Extension, 2021. https://extension.umd.edu/resource/controlled-atmosphere-storage-apples#:~:text=Controlled%20atmosphere%20(CA)%20storage%20is,life%20of%20stored%20apple%20fruits. (accessed Feb. 13, 2023).

[29] A. Weber, F. R. Thewes, R. de O. Anese, V. Both, E. P. Pavanello, and A. Brackmann, "Dynamic controlled atmosphere (DCA): interaction between DCA methods and 1-methylcyclopropene on 'Fuji Suprema' apple quality," Food Chem, vol. 235, pp. 136–144, Nov. 2017, doi: 10.1016/j.foodchem.2017.05.047.

[30] "U.S.: Stemilt uses mobile hydrocoolers to boost cherry shelf life," freshfruitportal.com, 2015. https://www.freshfruitportal.com/news/2015/06/24/u-s-stemilt-uses-mobile-hydrocoolers-to-boost-cherry-shelf-life/ (accessed Feb. 07, 2023).

[31] "United States Standards for Grades of Apples," 2019.

[32] US Apple Association, "2019 Production & Utilization Analysis," 2019. [Online]. Available: www.usapple.org.

[33] Tree Top, "Our History." https://www.treetop.com/consumer/our-brand/our-story/ (accessed Jan. 31, 2023).

[34] K. Lord, "Prosser bulk winemaking operation poised to expand with growing demand," Tri-Cities Area Journal of Business, 2018. https://www.tricitiesbusinessnews.com/2018/02/four-feathers/ (accessed Feb. 15, 2023).

[35] "Ground-harvested fruit, with care, OK for cider use," Fruit Growers News, Feb. 18, 2020. https://fruitgrowersnews.com/article/ground-harvested-fruit-with-care-ok-for-cider-use/ (accessed Dec. 15, 2022).

[36] H. K. Bal, C. Adams, and M. Grieshop, "Evaluation of Off-season Potential Breeding Sources for Spotted Wing Drosophila (Drosophila suzukii Matsumura) in Michigan," J Econ Entomol, vol. 110, no. 6, pp. 2466–2470, Dec. 2017, doi: 10.1093/jee/tox252.

[37] "Orchard Floor Management," WSU Tree Fruit Comprehensive Tree Fruit Site. https://treefruit.wsu.edu/orchard-management/orchard-floor-management/ (accessed Feb. 16, 2023).

[38] Y. Afzal Beigh, A. M. Ganai, and H. A. Ahmad, “Utilisation Of Apple Pomace As Livetock Feed: A Review,” The Indian Journal of Small Ruminants, vol. 21, no. 2, pp. 165–179, 2015, doi: 10.5958/0973-9718.2015.00054.9.

[39] “Weekly Shipments (Movement) - Pear.” Accessed: Jan. 16, 2023. [Online]. Available: https://usda.library.cornell.edu/concern/publications/qb98mf520?locale=en&page=2#release-items

[40] “Weekly Shipments (Movement) - Cherry AMS,” United States Department of Agriculture, Agricultural Marketing Service. https://usda.library.cornell.edu/concern/publications/8s45q885j?locale=en (accessed Feb. 15, 2023).

[41] “National Apple Processing Report.” Accessed: Jan. 16, 2023. [Online]. Available: https://usda.library.cornell.edu/concern/publications/2j62s492k?locale=en#release-items

[42] “Quick Stats: APPLES, NOT SOLD - PRODUCTION, MEASURED IN LB, 2017-2021,” United States Department of Agriculture, National Agricultural Statistics Service.

[43] L. Long and J. Olsen, “Sweet Cherry Cultivars for Brining, Freezing, and Canning in Oregon Processing Cherry Production in Oregon History,” 2013.

[44] S. P. Galinato and R. K. Gallardo, “2015 Cost Estimates of Establishing, Producing, and Packing Bing Sweet Cherries in Washington State,” 2015.

[45] E. Gołębiewska, M. Kalinowska, and G. Yildiz, “Sustainable Use of Apple Pomace (AP) in Different Industrial Sectors,” Materials, vol. 15, no. 5. MDPI, Mar. 01, 2022. doi: 10.3390/ma15051788.

[46] S. Rust and D. Buskirk, “Feeding Apples or Apple Pomace in Cattle Diets,” 2008. Accessed: Dec. 07, 2022. [Online]. Available: https://www.canr.msu.edu/uploads/236/58572/FeedingApplesorApplePomace.pdf

[47] KW Alternative Feeds, “Apple Pomace.” Accessed: Dec. 07, 2022. [Online]. Available: https://www.kwfeeds.co.uk/uploads/files/apple-pomace.pdf

[48] D. Miller, “Cyanide Poisoning of Livestock from Cherry Tree Leaves,” The Pennsylvania State University Extension, 2018. https://extension.psu.edu/cyanide-poisoning-of-livestock-from-cherry-tree-leaves (accessed Feb. 15, 2023).

[49] R. Czubaszek, A. Wysocka-Czubaszek, and R. Tyborowski, “Methane Production Potential from Apple Pomace, Cabbage Leaves, Pumpkin Residue and Walnut Husks,” Applied Sciences (Switzerland), vol. 12, no. 12, Jun. 2022, doi: 10.3390/app12126128.

[50] T. Mathison, “Making World Famous Compost,” Stemilt, 2019. https://www.stemilt.com/stem-blog/making-world-famous-compost/ (accessed Feb. 15, 2023).

[51] D. of Ecology, “Fact Sheet for NPDES Permit No. WA-000243-7 Tree Top, Inc. Selah Facilities Date of this Fact Sheet,” 2012.

[52] “Fact Sheet for Fresh Fruit Packing Draft General Permit,” 2021. [Online]. Available: https://wq.ecology.commentinput.com/?id=mBGE7

[53] E. Masanet, E. Worrell, W. Graus, and C. Galitsky, “Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry an ENERGY STAR ® Guide for Energy and Plant Managers,” 2008.

4. Potatoes Supply Chain Overview

The Washington potato supply chain includes farmers, packers, processors, and multiple markets for an array of products. As shown in Figure A-2.15, the supply chain begins by harvesting potatoes on farms. After harvest, potatoes are stored in sheds located near farms for up to one year. Fresh potato packers typically operate as an extension onto storage sheds, so they are also located near farms. As shown in Figure A-2.16, most potatoes are sent to processing plants [1]. Primary potato products from Washington processors include frozen French fries, dehydrated potatoes, chilled ready-to-eat dishes and IQF (individually-quick-frozen) potato pieces. Starch slurries, which are a byproduct of processing, can also be sold to make food ingredients and industrial supplies.

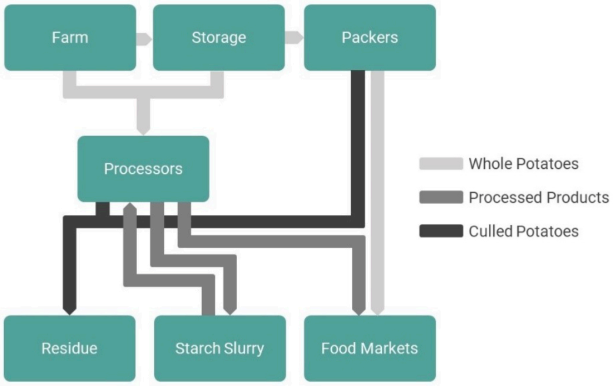

Figure A-2.15: Potato Supply Chain

The Washington potato supply chain includes farmers, packers, processors, and multiple markets for an array of products. As shown in Figure A-2.15, the supply chain begins by harvesting potatoes on farms. After harvest, potatoes are stored in sheds located near farms for up to one year. Fresh potato packers typically operate as an extension onto storage sheds, so they are also located near farms. As shown in Figure A-2.16, most potatoes are sent to processing plants [1]. Primary potato products from Washington processors include frozen French fries, dehydrated potatoes, chilled ready-to-eat dishes and IQF (individually-quick-frozen) potato pieces. Starch slurries, which are a byproduct of processing, can also be sold to make food ingredients and industrial supplies.

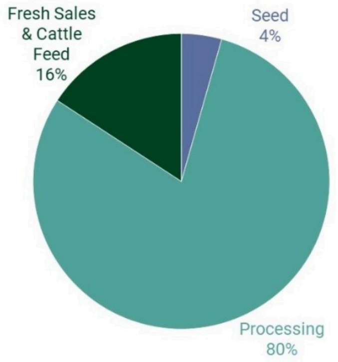

Figure A-2.16: Potato Sales in Washington and Oregon by Volume, 2019 – 2021

Agricultural practices for potatoes vary across Washington. As shown in Figure A-2.17, most Washington potatoes are grown in Eastern Washington [2]. Potatoes in this area are typically grown in 3- or 4-year rotations with a variety of grains, vegetable, and hay crops that often include alfalfa, field corn, sweet corn, beans, onions, carrots, and wheat [3]. Rotations in Northwest Washington are typically three years and may include field corn, vegetables, and berries.

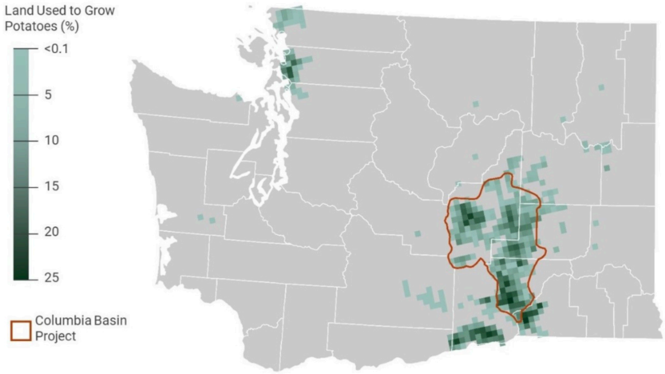

Figure A-2.17: Potato cultivation in Washington, 2021

Several types of potatoes are grown in Washington, but the most important varieties are Russet potatoes which are preferred by the state's potato processing industry due to their high specific gravity and large size [4]. Between 2016 and 2022, 80% of all potatoes grown in Washington were Russets, while white potatoes accounted for just 12%, red and blue potatoes 5%, and yellow potatoes 3% . Russet potatoes can be further divided into several varieties including Burbank, Nortkotah, Umatilla, Ranger, and several others [1]. In 1991, 83% of potatoes were planted to Russet Burbank, but by 2016 just 31% were planted to Burbank [5], as other varieties have recently become more popular for several reasons including appearance, storage characteristics, and resistance to diseases and pests. Farms in the south Columbia Basin typically grow potato varieties that are delivered fresh to processors, instead of stored [3]. Farms in Northwest Washington specialize in growing potatoes for the fresh market, with about half of the acreage being planted to red potatoes [3]. Potato varieties are also susceptible to rapid changes in market conditions. The widespread outbreak of covid-19 in 2020 resulted in a reduced demand for French fries from restaurants [6]. Between 2019 and 2021, the percentage of acres planted to Russet for all of Washington fell from 84% to 75%.

Major irrigation works, like the Columbia Basin Project shown in Figure A-2.17, make potato farming feasible in the arid shrub steppe environment of Eastern Washington [7]. The Columbia Basin Project distributes water from the Columbia River through a series of canals and reservoirs from the Grand Coulee Dam to Pasco [8]. It is particularly significant, as it supplied water to 62% of the state's potato acres in 2021. Another 31% of potato acreage was grown in a combination of state and privately-operated irrigation projects in Eastern Washington. Some areas, like the Horse Heaven Hills, along the Columbia River in Benton County have at least partially used ground water for irrigation in the past although the historic usage is not considered sustainable over the long term [9]. While not on the scale of the Columbia Basin Project, private projects that draw water from the Columbia, Snake, and Yakima Rivers supply a significant

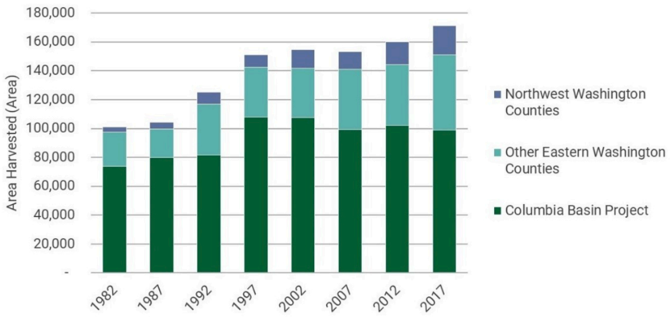

Figure A-2.18: Potato Acreage over time

Over the last 40 years, the area used to grow potatoes has changed significantly. As shown in Figure A-2.18, acreage increased in areas throughout the state between 1982 and 1997 [11]–[14] [15]–[18]. Since 1997, acreage in the Columbia Basin has decreased slightly while acreage has increased in other parts of Eastern Washington and Western Washington. Over this same period, yields have also increased substantially. Between 1957 and 2007, the average Washington Potato yield increased by an average of 7% per year [3].

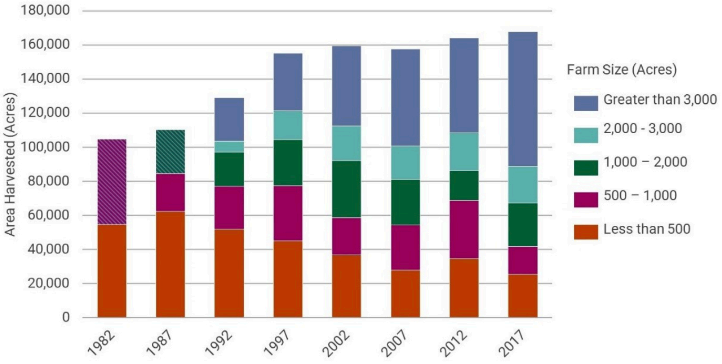

Figure A-2.19: Potato acres by farm size

One consistent trend in potato cultivation has been the increasing size of farms. As shown in Figure A-2.19, even as total potato acreage increased, the amount of acreage in farms greater than 3,000 acres has increased [19]–[22] [23]–[26]. In 1982, approximately half of total potato acres were grown in farms with less than 500 acres. While total acreage grew rapidly until 1997, the total amount of acres in the less than 500 acres category fell. In 2017, acreage in farms with less than 500 acres was less than half that of 1982, despite total acreage increasing 60%.

4.1 Potato Packers & Storage

For up to a year, potatoes are stored in sheds, which regulate temperature, humidity and airflow to prevent spoilage, moisture loss, and conversion of starches to sugars in the potatoes [27]–[30]. A representative from Lamb Weston described the objective of storage as tricking potatoes into thinking they're dormant during winter in the ground and waiting to sprout in the spring. Depending on the specifications of end users and the type of potato, they are stored between 38-50 degrees Fahrenheit [27]. There are no databases that track the locations of storage sheds, but it can generally be understood that sheds are close to farms. It is not uncommon for farms to own their own storage sheds, although some potatoes are stored at on-site storage owned by processors.

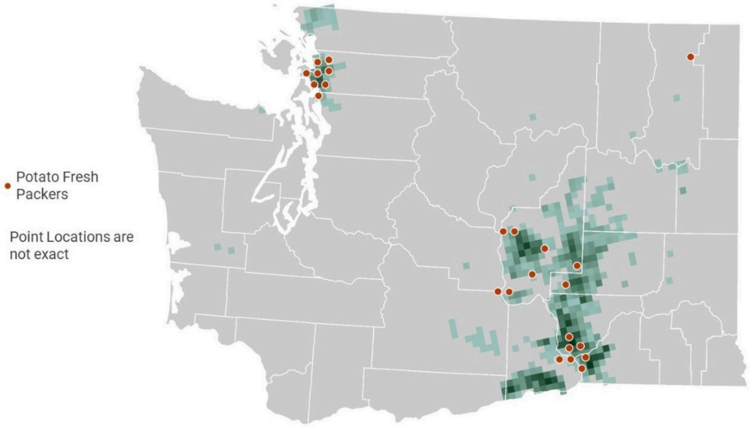

Figure A-2.20: Potato fresh packers in Washington

As shown in Figure A-2.20, potato packers are located throughout the Columbia Basin and the smaller potato growing region in Western Washington. The packers list may not be comprehensive, as it was from an industry trade organization [31]. Similar to storage sheds, fresh pack facilities are located near potato farms. Packing includes washing with water and often fumigants, sorting potatoes by size, optically inspecting them for quality issues, and packing [32]. Depending on the defect, culled potatoes from fresh pack facilities may still be sold for the processing market.

4.2 Potato Processors

Washington has twelve primary potato processing plants and two plants that process the waste starch slurry from processors into value added products. As shown in figure Figure A-2.21, all Potato processors are located in the Columbia Basin with clusters around the Tri-Cities (Richland and Pasco), Quincy, and Moses Lake/Warden/Othello and a lone facility in Connell.

Figure A-2.21: Washington Potato Processors

Most processors make French fries, and account for a large majority of the state's total capacity. Key processes include grading and washing, peeling, slicing, blanching, frying, freezing, and packing [33]. Water permit data from the Washington Department of Ecology was used to identify facilities and their characteristics [34]. Three companies operate fry plants: Lamb Weston operates 5, JR Simplot operates 2, and McCain Foods operates 1. Lamb Weston also has the largest total capacity, as all the fry plants have relatively similar capacities that range between 231,000 and 413,000 tons per year. Optical sorters are used to find defects in the potatoes. Instead of culling an entire defective potato, typically just a small section of the potato is removed and the pieces that are not large enough to make fries are sent to a secondary line that makes "formed" products like hash browns. After potatoes are washed and peeled, potatoes are sprayed as they go through slicing. The water recovered from this step can be sold to other companies as a starch slurry.

Two processors primarily produce dehydrated potatoes. Key processes include washing, peeling, precooking and cooking, mashing, and drum drying. The manufacture of dehydrated potatoes is relatively energy intensive, as the energy input to process one ton of potatoes is almost triple the amount required for frozen French fries. Because dehydrated potatoes are made into small flakes, they are not dependent on sourcing potatoes that produce large slices, allowing them to receive culled potatoes from the fresh pack industry.

Starch processors upgrade the slurry received from other plants. The processor in Richland produces a wide variety of food ingredients. Notably, the Lamb Weston in Richland purchases a French fry batter to make extra-crispy “stealth fries”, meaning the starch is returned to its origin [35]. The plant in Moses Lake manufactures chemicals for the paper industry [36]. Ingredion currently owns both facilities.

4.3 Waste Biomass Inventory

Waste biomass is generated at several points along the supply chain and includes culled potatoes and rejected potato pieces from processors. No use cases were found for the above ground biomass of the plants. Potatoes are harvested mechanically from the ground and transported to storage sheds where they are sorted before being stacked in piles. Sorting is repeated before either packing or processing. Fresh packers only market the most-desirable looking potatoes, as it is expected that customers can individually inspect each tuber. Rejected potatoes may be sent to processors or culled. Processors work to minimize rejected biomass by selectively cutting out bad spots in potatoes and using an efficient peeling technique that uses steam and pressure to remove the skin. Small potato pieces that are too small for French fries or other larger cuts are used to make formed potato products like hash browns. No data on cull rates of potatoes was found for potato fresh packers. Processors can be expected to reject 15-40% of all incoming biomass depending on their process technology [37].

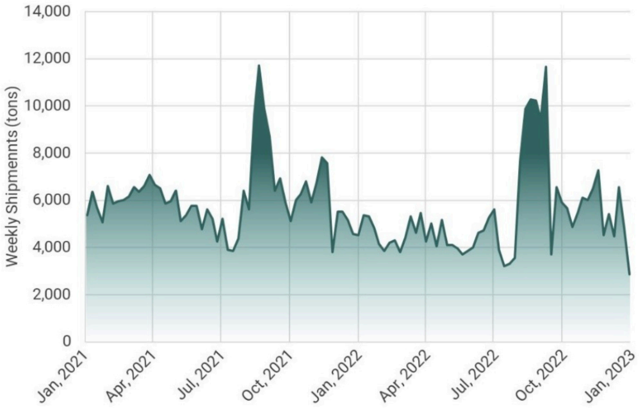

Figure A-2.21: Washington Potato Processors

Relative to other fruits and vegetables, the supply of potatoes throughout the year is relatively stable due to their long storage life. As shown in Figure A-2.22, there is a jump in potato shipments near harvest, as farmers deliver some of their potatoes to commercial facilities with storage capacity [38]. For most of the year, weekly potato shipments from Washington range from 7,000 tons during the months following harvest to approximately 4,000 tons during the summer.

4.4 Biomass Uses

While a complete inventory of potato biomass is not available, it is likely that it is almost exclusively sold for cattle feed. Potatoes are high in starch, and can function similar to grains in cattle diets, although their high moisture content can limit cattle performance and are expensive to transport [39]–[42]. Potatoes are also low in necessary nutrients like protein, calcium, and fiber, so farmers would need to supplement with other foods. At a feed rate of 3lbs of potatoes per 100lbs of animal weight, a typical cow could consume approximately 48lbs pounds of potato culls per day in a healthy diet [40]. Several potato companies are also involved in the cattle and dairy industries. These cross-industry ties suggest that feeding cattle potatoes is partly a matter of convenience. J.R. Simplot, known for pioneering frozen French fries, also owns a cattle feedlot in Burbank. Lamb Weston, the largest potato processing company in the state, owns a dairy in Paterson.

Potatoes can be fermented and used to produce fuels like biogas [43].

4.5 Energy

Potato processing is energy-intensive and typically includes high-heat applications for steam, drying, and frying. Energy consumption values are not available on a plant basis, although air permit records for the Lamb Weston French fry plant in Hermiston, OR, the Oregon Potato dehydrated potato plant in Boardman, OR and other studies can be used to inform initial assessments [33], [44], [45]. In both Hermiston and Boardman, natural-gas fired plants supply food processors with thermal energy via steam. The Lamb Weston plant in Hermiston has steam delivered by the adjacent Hermiston Generating Plant, owned by Perennial Power [46]. The Coyote Springs Natural Gas Cogeneration Facility in Boardman supplies steam to several industrial customers [47].

4.6 Water

Water use and output varies by plant, as potato processing plants manage different water streams throughout their plants. Some plants, like Lamb Weston in Richland, operate their own wastewater treatment plants [48]. Most wastewater treatment plants dispose of at least some of their water via land application.

Potato References

[1] "Quick Stats," United States Department of Agriculture, National Agricultural Statistics Service. https://quickstats.nass.usda.gov/ (accessed Feb. 28, 2023).

[2] "CropScape," United States Department of Agriculture, National Agricultural Statistics Service, 2021.

[3] K. Hills, H. Collins, G. Yorgey, A. Mcguire, and C. Kruger, "Safeguarding Potato Cropping Systems in the Pacific Northwest Through Improved Soil Health," 2018.

[4] "Potato Variety Selection," Oregon State University. https://cropandsoil.oregonstate.edu/potatoes/potato-variety-selection (accessed Feb. 21, 2023).

[5] N. Richard Knowles and M. J. Pavek, "Potato Cultivar Yield and Postharvest Quality Evaluations," 2020. [Online]. Available: http://www.potatoes.wsu.edu/http://www.pvmi.org

[6] Z. Jennings, "COVID-19 report: Potato industry still feeling effects of foodservice shutdowns," Spudman, 2020.

[7] "Project Map," Columbia Basin Development League. https://www.cbdl.org/project-map/ (accessed Feb. 20, 2023).

[8] W. J. Simonds, "The Columbia Basin Project," 1998.

[9] "Appraisal Study: DNR Paterson Irrigation Project," 2012.

[10] "AgriNorthwest - About Us," AgriNorthwest. https://www.agrinorthwest.com/Home/About (accessed Feb. 20, 2023).

[11] "1982 Census of Agriculture - County Data: Washington, Table 25. Cotton, Tobacco, Soybeans, Dry Beans and Peas, Potatoes, Sugar Crops, and Peanuts: 1982 and 1978," 1982.

[12] "1987 Census of Agriculture - County Data: Washington, Table 25. Cotton, Tobacco, Soybeans, Dry Beans and Peas, Potatoes, Sugar Crops, and Peanuts: 1987 and 1982," 1987.

[13] "1992 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 27. Cotton, Tobacco, Soybeans, Dry Beans and Peas, Potatoes, Sugar Crops, and Peanuts: 1992 and 1987," 1992.

[14] "1997 Census of Agriculture - County Data: Washington, Table 27. Cotton, Tobacco, Soybeans, Dry Beans and Peas, Potatoes, Sugar Crops, and Peanuts: 1997 and 1992," 1997.

[15] "2002 Census of Agriculture - County Data: Washington, Table 25. Cotton, Tobacco, Soybeans, Dry Beans and Peas, Potatoes, Sugar Crops, and Peanuts: 2002 and 1997," 2002.

[16] "2007 Census of Agriculture - County Data: Washington, Table 30. Vegetables, Potatoes, and Melons Harvested for Sale: 2007 and 2002," 2007.

[17] "2012 Census of Agriculture - County Data: Washington, Table 29. Vegetables, Potatoes, and Melons Harvested for Sale: 2012 and 2007," 2012.

[18] "2017 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 29. Vegetables, Potatoes, and Melons Harvested for Sale: 2017 and 2012," 2017.

[19] "1982 Census of Agriculture - State Data: Washington, Table 41. Specified Crops by Acres Harvested: 1982 and 1978," 1982.

[20] "1987 Census of Agriculture - State Data: Washington, Table 44. Specified Crops by Acres Harvested: 1987 and 1972," 1987.

[21] "1992 Census of Agriculture - State Data: Washington, Table 42. Specified Crops by Acres Harvested: 1992 and 1987," 1992.

[22] "1997 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 42. Specified Crops by Acres Harvested: 1997 and 1992," 1997.

[23] "2002 Census of Agriculture - State Data: Washington, Table 34. Specified Crops by Acres Harvested: 2002 and 1997," 2002.

[24] "2007 Census of Agriculture - State Data: Washington, Table 34. Vegetables, Potatoes, and Melons Harvested for Sale: 2007 and 2002," 2007.

[25] "2012 Census of Agriculture - State Data: Washington, Table 38. Vegetables, Potatoes, and Melons Harvested for Sale: 2012 and 2007," 2012.

[26] "2017 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 36. Vegetables, Potatoes, and Melons Harvested for Sale: 2017 and 2012," 2017.

[27] R. E. Voss, K. G. Davis, and H. Timm, "Proper Environment for Potato Storage."

[28] T. L. Brandt, G. Kleinkopf, N. Olsen, and S. Love, "Storage Management for Umatilla Russet Potatoes."

[29] T. L. Brandt, G. Kleinkopf, N. Olsen, and S. Love, "Storage Management for Gem Russet Potatoes," 2004.

[30] W. M. Iritani and W. C. Sparks, "Potatoes: Storage And Quality Maintenance in the Pacific Northwest," 1985.

[31] "Fresh Potatoes," Washington State Potato Commission. https://www.potatoes.com/category/fresh-potatoes (accessed Feb. 28, 2023).

[32] "Fresh Pack Potato Plant," Prairie Gold Produce, 2019. https://www.youtube.com/watch?v=lfNI6oAqQtM (accessed Feb. 23, 2023).

[33] E. Masanet, E. Worrell, W. Graus, and C. Galitsky, "Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry An ENERGY STAR ® Guide for Energy and Plant Managers," 2008.

[34] "Water Quality Permitting and Reporting Information System (PARIS)," Washington Department of Ecology. https://apps.ecology.wa.gov/paris/PermitLookup.aspx (accessed Feb. 15, 2023).

[35] "French Fries That Don't Show Up On Radar?," Spokesman Review, 1995. Accessed: Feb. 06, 2023. [Online]. Available: https://www.spokesman.com/stories/1995/may/20/french-fries-that-dont-show-up-on-radar/

[36] "Ingredion Acquires Western Polymer Expanding Capacity For Higher-Value Specialty Ingredients," Global News Wire, 2019.

[37] J. S. van Dyk, R. Gama, D. Morrison, S. Swart, and B. I. Pletschke, "Food processing waste: Problems, current management and prospects for Utilisation of the lignocellulose component through enzyme synergistic degradation," Renewable and Sustainable Energy Reviews, vol. 26. pp. 521–531, 2013. doi: 10.1016/j.rser.2013.06.016.

[38] "Weekly Shipments (Movement) - Potatoes, Table," United States Department of Agriculture, Agricultural Marketing Service. https://usda.library.cornell.edu/concern/publications/f7623c62m?locale=en (accessed Feb. 28, 2023).

[39] R. Rasby and J. Martin, "Understanding Feed Analysis," Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

[40] M. Snowdon, “Feeding Potatoes to Cattle,” Government of New Brunswick. https://www2.gnb.ca/content/gnb/en/departments/10/agriculture/content/livestock/cattle/potatoes.html#:~:text=Because%20of%20their%20very%20low,animal%20performance%20or%20feed%20efficiency. (accessed Dec. 07, 2022).

[41] U. of N.-L. Institute of Agriculture and Natural Resources, “Processing Potatoes for Livestock Feed.” https://cropwatch.unl.edu/potato/processing_for_feed (accessed Dec. 07, 2022).

[42] C. Dahlen, A. Robinson, R. Larsen, and E. Crawford, “Potatoes Possible Source of Cattle Feed,” North Dakota State University, Sep. 24, 2012.

[43] C. K. Locker, “Residual biomass Utilisation in the potato and sugar beet processing industry: evaluation from a circular perspective,” 2021.

[44] “Air Permit for Lamb Weston, Permit No. 30-0075-ST-01,” 2018.

[45] “Air Permit for Oregon Potato Company, Permit No. 25-0002-SI-01,” 2018.

[46] “Hermiston Generating Plant,” Perennial Power, 2020. http://www.perennialpower.net/Portfolio/Hermiston-Generation-Plant/ (accessed Feb. 27, 2023).

[47] “Coyote Springs Cogeneration Project,” 1994.

[48] “Fact Sheet for NPDES Permit No. WA0052141 ConAgra Foods Lamb-Weston Richland Facility,” 2013.

5. Grapes Supply Chain Overview

The supply chain for grapes in Washington results in either juice or wine depending on the type of grape. As shown in Figure A-2.23, the supply chain begins during harvest at vineyards during the fall. Following harvest, grapes are quickly crushed and processed. Washington grape products are available to consumers throughout the year. Grape juice is pasteurized, so it can last until the next harvest season and wines are typically aged several years.

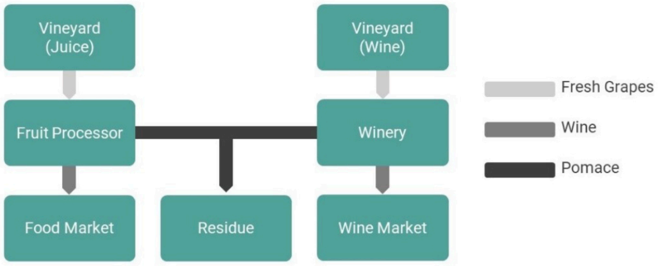

Figure A-2.23: Grape supply chain

4.4 Vineyards

As shown in Figure A-2.24, almost all commercial vineyards in Washington are grown east of the Cascade Mountain range, particularly in the Horse Heaven Hills, Yakima Valley, and Walla Walla areas [1]. According to the 2017 census, Benton County had the most acres of grapes followed by Yakima County [2]. Together, those two counties comprise the entire Yakima Valley. Southern Benton County and Klickitat County have a significant amount of grapes in the Horse Heaven Hills near Paterson.

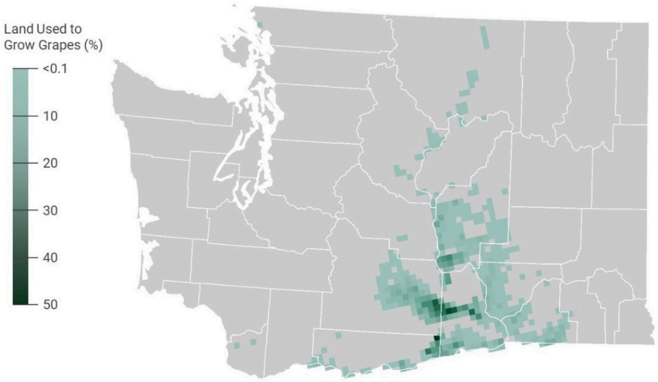

Figure A-2.24: Washington Vineyards in 2021

Most of the grapes in Grant County are in the Wahluke Slope area, near Mattawa. The Grapes in Franklin County are dispersed over the Columbia Plateau, largely in the White Bluffs area. Most grapes in Walla County are near the city of Walla Walla.

Over the last 40 years, the total area used to grow grapes in Washington has increased substantially. As shown in Figure A-2.25, Washington had 27,000 acres of vineyards in 1982. By 2017, that area had nearly tripled to a total acreage of 78,000 acres [3]–[6]. Over that period, land held in small vineyards, with less than 100 acres, has remained stable, while most growth has been from mid-sized and large vineyards.In 1982, vineyards with more than 100 acres had 12,000 total acres, by 2017 that acreage had more than quintupled to 64,000 acres. Compared to other types of farms in Washington, vineyards are typically operated as relatively small farms. For instance, less than 20% of potatoes are grown on

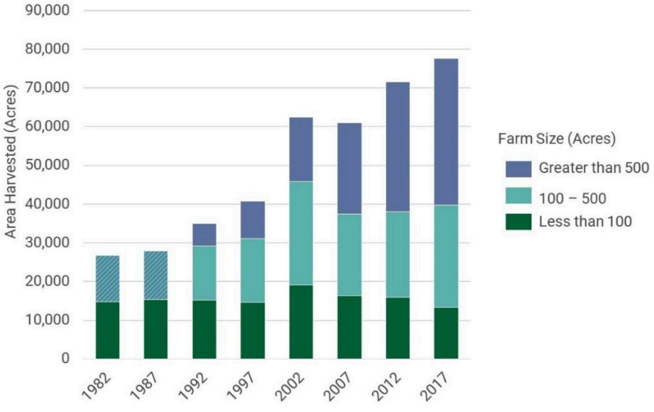

Figure A-2.25: Grape harvest by Farm Size

4.5 Varieties

Grapes within Washington fall into two main categories: juice and wine. These categories are distinct, and each consists of several varieties. While crop outcomes are dependent on an array of factors including variety, management practices, climate, and soil, wine grapes typically have lower yields but greater gross returns because of their higher value [8]–[10]. Wine grapes can be further divided into red and white subcategories. Each type of wine grape is grown throughout Washington, although some areas or vineyards tend to specialize in one or the other [11]. Processing can also be variable depending on the grape variety. During early fermentation, grape skins are used to impart tannins in red wines. White wines are fermented without the skins. Rosé wines are a subcategory of red wines [12]. They use red wine grapes but are fermented similarly to white wines with little to no contact from the grape skins. The longer rose wines are in contact with the grape skins, the darker they become.

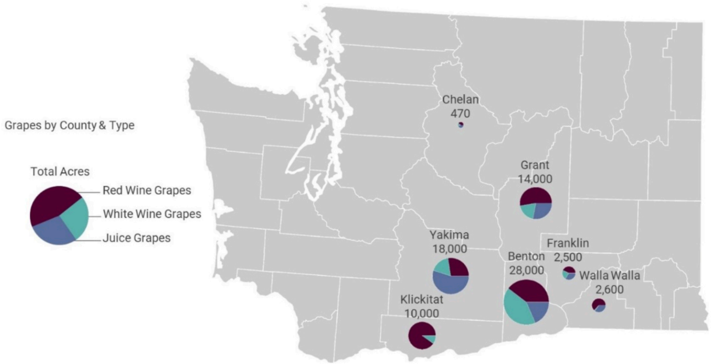

Figure A-2.26: Grapes by Types and County

Most grape acreage in Washington is used to grow wine grapes, but the distribution of grapes is not consistent throughout the state. As shown in Figure A-2.26, most juice grapes are grown in the Yakima Valley, which includes the grapes in Yakima County and some of the grapes in Benton County [11]. Red wine grapes are the most prominent type of wine grape, especially in Walla Walla and Klickitat counties, which have almost no white wine grapes. The distribution of grape types is dependent on several factors. For instance, the facility database establishes that Yakima Valley is home to all the state's grape juice processors, so it is likely that it is most convenient to contract with more local growers. Climate is a major factor for wine grapes. It is generally considered that warmer climates are suited for red wines in Washington, so areas like the Horse Heaven Hills and Walla Walla Valley grow predominantly red wine grapes [13].

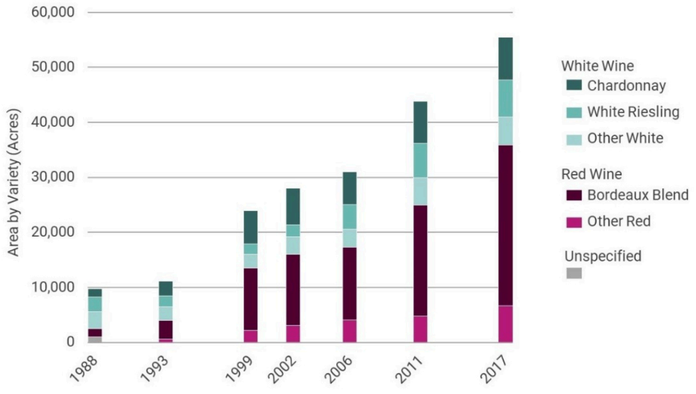

Figure A-2.27: Wine Grape Varieties by Year

The Washington grape industry is relatively immature compared to other parts of the world with large production capacities. It is valuable to consider how the industry has changed as it has matured over the last 40 years, and to consider whether we should expect significant changes to the industry in the near future. Figure A-2.27 shows the distribution of red and white wine grape acreage by year [11], [14]. In 1988, most wine grapes in Washington were white wine grapes, and the most popular variety was white Riesling [14]. By 1999, total red wine grapes had overtaken whites, and Chardonnay had become the most popular variety. By 2011, segment growth of red wine grapes had continued to outpace white wine grapes and Cabernet Sauvignon, a Bordeaux variety, had become the most popular variety in the state. Current projects suggest that the pace of the growth over the last several decades is likely slowdown in coming years as wine has lost market share to other alcohol [15].

The impact of variety selection on the grape industry may be important relative to symbiosis. Wine grapes are smaller than juice grapes but have a higher sugar content and thicker skins [16]. And because red wines are aged on their skins, grapes that produce especially thick skins can be favored in certain applications [17]. All these factors impact the amount and quality of excess biomass produced by the grape industry. Energy inputs may also be variable. Some grape juice is concentrated, which demands a large amount of heat [18]. Wine is often stored by wineries for several years before it is released, and during that period it must be stored in a climate-controlled warehouse [19], [20].

4.5 Varieties

Figure A-2.28 shows the locations of large grape processors in Washington in the facility database. All of them are in Eastern Washington, and the locations of most can be further defined as falling within the Yakima Valley. Four Juice processors are all located near the line between Yakima and Benton Counties in either Grandview or Prosser. In total, Washington has more than 1,000 wineries licensed by the state Liquor and Cannabis Board [21]. Not all of these are considered relevant for symbiosis. 20 large wineries, those that process more than 50,000 cases per year, are spread across Eastern Washington. The major clusters are in Prosser/ Grandview and the Tri Cities. The Horse Heaven Hills, Mattawa, George, and Walla Walla also have large wineries.

Figure A-2.28: Major Grape Processors in Washington

After harvest grapes are crushed and juiced, grape juice is sterilized and then packaged in sterilized and sealed bottles [10], [18]. In some instances, juice may be concentrated which requires heat to drive moisture from the juice. Depending on the plant and specific product, grape juice may be mixed with other ingredients. At wineries, crushing is followed by fermentation, ageing, and packaging [22].

Below are some useful terms that can be used to classify wineries and wines [23], [24]:

- **Estate**: wines in which all processes in the supply chain, from the vineyard to bottling, are executed by one company. Estate wines are made by wineries of all sizes. A winery may produce both estate wine and non-estate wines.
- **Custom Crush**: winery that executes parts of the wine production process for another company. Services may include crushing, fermenting, aging, and packaging, but vary by customer. All custom crush wineries are considered large wineries in Washington.
- **Label**: One company may produce wines under multiple labels, even when production is executed at one facility. The purpose for using multiple labels is often for one company to appeal to a broader spectrum of wine consumers. In other cases, a custom crush winery may produce wine for a customer under one label and their own wine under another.

Figure A-2.29: Capacity of Ste. Michelle Winery estates relative to total capacity in Washington.

The largest wine company based in Washington is Ste. Michelle Estates [25]. Within Washington Ste. Michelle labels include Chateau Ste. Michelle, Columbia Crest, 14 Hands, Snoqualmie, and Col Solare but they also own several other wineries in the United States and one in Italy [26], [27]. As one of the older wineries in Washington, they have long utilized much of the state's total grape production, peaking near 70% [28]–[36]. As shown in Figure A-2.29, total production from Ste. Michelle had closely mirrored overall Washington wine production until 2014. This has coincided with a shift in sentiment within the industry that Ste. Michelle's successes and failures are no longer indicative of the state's industry as a whole [37]–[39]. Despite recent woes, Ste. Michelle will likely continue to be Washington’s largest wine company for the foreseeable future.

4.6 Wine Value and Scale

Instead of seeking to maximize yields or total alcohol production, wineries may choose to emphasize subjective qualitative characteristics to maximize value. An advantage of this approach relative to symbiosis is that smaller facilities are not only commercial, but competitive with many other similar facilities. This competition leads to an environment that seeks innovation and is also flexible enough to implement new ideas quickly. In most other industries, the scale of many Washington wineries would be considered a pilot or demo scale, meaning that wineries are at a scale advantageous for experimentation [40].

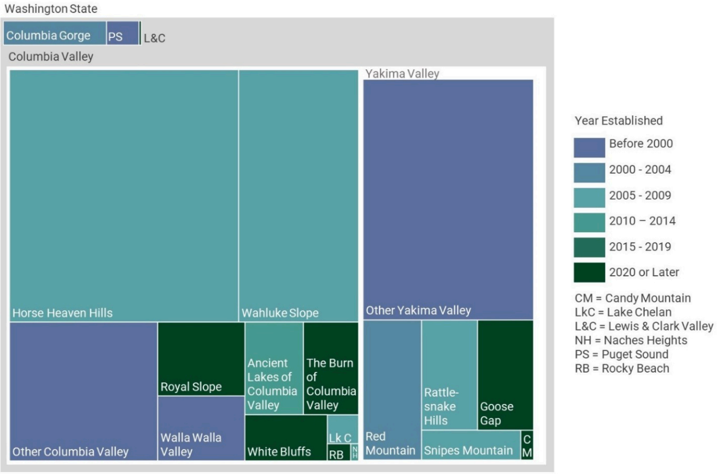

Figure A-2.30: Washington AVAs by the year they were founded and their current grape acreage

The establishment of Washington as a high-quality wine producing region has been the utmost priority of organizations like the Washington Wine Commission [41]. Historically, Washington has been recognized for producing low-priced premium quality wine [15], [42]. As the wineries within the region have become better established and consumers have become better educated, this perception has begun to change to a higher opinion. One indicator of this change is the recent establishment of small American Viticulture Areas (AVAs). AVAs are geographic areas that are used to specify the origin of wine. As shown in Figure A-2.30, the older AVAs within the state are large, for instance the Columbia Valley AVA encompasses almost all wine grapes within the state. Newer AVAs are smaller, and typically sub-AVAs of the Columbia Valley [43]. Often, they encompass a small area. For instance, Candy Mountain contains a single south-facing hillside. Wines from these AVAs are scarcer, meaning that their rarity can lead to higher value. This proliferation of small AVAs especially serves to benefit small estate vineyards and wineries who can monetize the sense of their connection to the land. This shift toward higher-value wines suggests that Washington’s diverse wineries will continue to persist, and that it is unlikely that consolidation will heavily impact the industry in the foreseeable future.

4.6 Biomass

Grape biomass includes seeds, stems, and skins discarded after juice or wine processing. Relative to other types of agricultural biomass, grape waste is produced in small quantities. As noted in the water permit fact sheet for the Welch’s plant in Grandview, approximately 90 pounds of waste is produced for every ton of grapes processed, just 4.5% of total incoming biomass [44]. At Welch’s waste generation rate, total grape biomass in 2021 would have been 13,000 tons. This value is likely slightly low, as wine grapes often have thicker skins than juice grapes.

The seasonal availability of grape biomass is based around harvest in the fall. Grapes are crushed soon after harvest, and most of the biomass is available after crushing. Red wines are fermented on grape skins for approximately one month, depending on the maker’s preferences, so much of the red wine biomass becomes available later.

According to water permits indexed for the facility database, most grape biomass is either landfilled, used for cattle feed, or mulched and used as compost. Limited information is available about the specific qualities of grape biomass.

4.6 Water

According to Washington's general permit for wineries, on average wineries use approximately 6 gallons of water for each gallon of wine produced [45]. Wastewater from grape processing can be handled by local wastewater plants in some cases, as Washington does not require wineries that produce less than 7,000 cases to have water permits. But larger wineries often have their own wastewater treatment plants. Several projects they may be considered examples of symbiosis have already been undertaken by the industry. Northstar Winery in Walla Walla is a small winery with an annual production capacity of 10,000 cases. In 2019, they became the first winery in Washington to use BioFiltro's worm bedsin its water treatment plant [46]. West Richland and Kennewick both have wine wastewater pretreatment plants [47]. These plants help attract new businesses by reducing the capital costs necessary for new wineries near the treatment plants.

4.6 Energy

Energy inputs for processing grapes depend on whether the grapes are used for juice or wine. For grape juice processing, the juice must be sterilized, which is typically accomplished using steam [18]. If the juice is concentrated, additional heat will be required. At wineries, just the packaging is sterilized for most types of wine. Atmospheric temperature control at wineries is important throughout fermentation and aging [48], [49]. Aging is done in large warehouses and is an important component of the wine industry. Wines typically aged a minimum of 1 year, and often more, before release. Outside of Washington, wineries have used alternative energy sources to heat their facilities, like geothermal [50].

Grape References

[1] “CropScape,” United States Department of Agriculture, National Agricultural Statistics Service, 2021.

[2] “2017 Census of Agriculture. Volume 1. Washington. Chapter 2. Table 31. Fruits and Nuts: 2017 and 2012,” 2017.

[3] “1987 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 45. Specified Fruits and Nuts by Acres: 1987 and 1982,” 1987.

[4] “2017 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 37. Specified Fruits and Nuts by Bearing and Nonbearing Acres: 2017 and 2012,” 2017.

[5] “2007 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 35. Specified Fruits and Nuts by Bearing and Nonbearing Acres: 2007 and 2002,” 2007.

[6] “1997 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 42. Specified Crops by Acres Harvested: 1997 and 1992,” 1997.

[7] “2017 Census of Agriculture. Volume 1. Washington. Chapter 1. Table 36. Vegetables, Potatoes, and Melons Harvested for Sale: 2017 and 2012,” 2017.

[8] M. Hansen, “Washington picks big wine, juice grape crops,” Good Fruit Grower, 2015. https://www.goodfruit.com/washington-picks-big-wine-juice-grape-crops/ (accessed Mar. 13, 2023).

[9] “2021 Grape Production Report,” 2022.

[10] E. Degerman, “Concords rebound: Juice grape growers step up to meet demand,” Tri-Cities Area Journal of Business, 2020. https://www.tricitiesbusinessnews.com/2020/06/concords-rebound-focus/ (accessed Mar. 13, 2023).

[11] C. Mertz, D. Koong, and S. Anderson, “Washington Vineyard Acreage Report2017,” 2017.

[12] “The difference between White wine, Rose and Red Wine?,” Napa Reserva, 2014. http://www.napareserva.com/2014/03/what-is-the-difference-between-white-wine-rose-wine-and-red-wine/ (accessed May 22, 2023).

[13] “Washington AVA Overviews,” Washington Wine Commission. https://www.washingtonwine.org/resources/?_resource_type=ava (accessed Mar. 09, 2023).

[14] R. J. Folwell and M. A. Castaldi, “Bulk Winery Investment And Operating Costs,” 2004.

[15] R. McMillan, “State of the US Wine Industry 2023,” 2023.

[16] Madeline Puckette, “Cultivation: Table Grapes vs. Wine Grapes,” Wine Folly. https://winefolly.com/tips/table-grapes-vs-wine-grapes/ (accessed May 22, 2023).

[17] Rosamie, “The Pros and Cons of Thick Skinned Grapes in Wine Production,” Slo Wine Country, 2022.

[18] E. Masanet, E. Worrell, W. Graus, and C. Galitsky, “Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry an ENERGY STAR ® Guide for Energy and Plant Managers,” 2008.

[19] M. Malvoni, P. M. Congedo, and D. Laforgia, “Analysis of energy consumption: A case study of an Italian winery,” in Energy Procedia, Elsevier Ltd, Sep. 2017, pp. 227–233. doi: 10.1016/j.egypro.2017.08.144.

[20] G. Panaras, P. Tzimas, E. I. Tolis, G. Papadopoulos, A. Afentoulidis, and M. Souliotis, “Combined investigation of indoor climate parameters and energy performance of a winery,” Applied Sciences (Switzerland), vol. 11, no. 2, pp. 1–15, Jan. 2021, doi: 10.3390/app11020593.

[21] “Licensee List,” Washington State Liquor and Cannabis Board, 2023. https://lcb.wa.gov/taxreporting/licensee-list (accessed May 21, 2023).

[22] M. Brown, “The Ultimate Guide to Winemaking,” The Wine Society, 2020. https://www.thewinesociety.com/discover/explore/regional-guides/winemaking-ultimate-guide (accessed May 22, 2023).

[23] “Can a custom crush client use estate bottled on their label?,” Wine Compliance Alliance, 2010.

[24] E. Saladino, “The Differences Between Estate, Estate Bottled and Single Vineyard Wines,” Wine Enthusiast, 2022.

[25] S. P. Sullivan, “Sold! What The Ste. Michelle Sale Means for Washington’s Wine Industry,” Beverage Industry Enthusiast, 2021. https://www.winemag.com/2021/07/12/ste-michelle-sale-washington-wine/ (accessed Mar. 09, 2023).

[26] W. B. Gray, “Washington Winery Sale Raises Questions,” Wine-Searcher, Jul. 2021. https://www.wine-searcher.com/m/2021/07/washington-winery-sale-raises-questions (accessed Feb. 08, 2023).

[27] “Estates & Partnerships,” Ste. Michelle Wine Estates. https://www.smwe.com/estates/ (accessed May 22, 2023).

[28] “2020 Altria Group, Inc. 10-K.”

[29] “2019 Altria Group, Inc. 10-K.”

[30] “2018 Altria Group, Inc. 10-K.”

[31] “2017 Altria Group, Inc. 10-K.”

[32] “2009 Altria Group, Inc. 10-K.”

[33] “2015 Altria Group, Inc. 10-K.”

[34] “2011 Altria Group, Inc. 10-K.”

[35] “2013 Altria Group, Inc. 10-K.”

[36] “Vintages: 30-Year Overview,” Washington Wine Commission, 2022. https://www.washingtonwine.org/resource/vintages-30-year-overview/ (accessed Mar. 09, 2023).

[37] C. Bitter, “Small and Mid-sized Wineries Drive Growth in Washington State,” Vintage Economics, 2022. https://www.vineconomics.com/blog/small-and-mid-sized-wineries-drive-growth-in-washington-state (accessed Mar. 09, 2023).

[38] R. Courtney and T. Mullinax, “Nuanced improvement for Washington wine industry,” Good Fruit Grower, 2022. https://www.goodfruit.com/nuanced-improvement-for-washington-wine-industry/ (accessed Mar. 09, 2023).

[39] W. B. Gray, “Washington Wine: A Tale of Two Industries,” Wine-Searcher, Mar. 2021. https://www.wine-searcher.com/m/2021/03/washington-wine-a-tale-of-two-industries (accessed Feb. 08, 2023).

[40] O. Olsson & B. Nykvist, “Demonstration plants and scale,” 2020.

[41] “About WA Wine,” Washington Wine Commission. https://www.washingtonwine.org/about-wa-wine/ (accessed May 22, 2023).

[42] C. Bitter, “Washington Grape Prices in Perspective,” Vine Economics, 2018. https://www.vineconomics.com/blog/washington-grape-prices-in-perspective (accessed May 22, 2023).

[43] “Established American Viticultural Areas,” Alcohol and Tobacco Tax and Trade Bureau, United States Department of the Treasury, 2022. https://www.ttb.gov/wine/established-avas (accessed May 20, 2023).

[44] “Fact Sheet for Welch Foods Grandview: State Waste Discharge Permit No. ST0009123,” 2017.

[45] “Winery General Permit,” 2018.

[46] “Northstar Winery Is First in Washington State to Employ BioFiltro BIDA® Wastewater Recycling System,” Wine Industry Advisor, 2019. https://www.spiritedbiz.com/northstar-winery-is-first-in-washington-state-to-employ-biofiltro-bida-wastewater-recycling-system/ (accessed May 20, 2023).

[47] S. Bassinger, “Cities build wine waste treatment plants to lure wineries,” Tri Cities Business Journal, 2017.

[48] P. Catrini, D. Panno, F. Cardona, and A. Piacentino, “Characterization of cooling loads in the wine industry and novel seasonal indicator for reliable assessment of energy saving through retrofit of chillers,” Appl Energy, vol. 266, May 2020, doi: 10.1016/j.apenergy.2020.114856.

[49] “Process efficiency in winery operations: a broad review of potentially beneficial techniques and technologies RESEARCH REPORT.” [Online]. Available: www.2xe.com.au

[50] “Geothermal Heating, Cooling System Helping Winery Crush Energy Costs,” HPAC Engineering, 2017. https://www.hpac.com/commercial/article/20929124/geothermal-heating-cooling-system-helping-winery-crush-energy-costs (accessed May 22, 2023).

Appendix A-3

Heat Sharing Potential from Select Ag Processors

1. Introduction

Heat is an almost universal need for residential, commercial and industrial buildings. Collectively the energy needed to heat these buildings requires a tremendous amount of resources like electricity and natural gas. At industrial facilities, heat is typically generated via combustion of natural gas, other fuels, or biomass [1]. Several tactics can be implemented to reduce energy consumption including improving unit-level energy efficiency, heat-recovery within a single facility, and heat-sharing among multiple facilities [2]. Among these options, heat sharing is the most complicated to use, but when implemented it is a mutually beneficial exchange of heat between companies that results in new revenue streams for heat suppliers and reduced fossil fuel demands for heat sinks. It is accomplished through the exchange of steam, heated liquids, or hot air between facilities.

Within the agricultural industry, common heat applications include cooking, drying, sterilization, cleaning, and space heating, which result in the generation of waste heat in the form of vapor, fumes, and wastewater [3], [4]. Additionally, mechanical equipment, like compressors for refrigeration units, don't require heat inputs, but may be a source of heat [4]. In general, high temperatures and large volumes of heat are the most desirable for sharing applications, but other factors are also important to consider like pressure, composition, and variations in availability [4]–[6]. Because heat-sharing relationships include two or more companies, it is necessary that all stakeholders are compatible with the heat being shared [5], [7]. For relationships that include agricultural processors especially, an important inconvenience for their partners may be daily variations in heat caused by breaks between batches or routine cleaning [8]. Many processors also only operate seasonally, and may not generate or require heat for months at a time. Most heat applications within the agricultural industry are considered "low grade-heat", as they are often below 300F, which is relatively cool compared to temperatures required for other industrial processes like smelters [9]–[11]. This means that agricultural processors can serve as both suppliers and sinks [1]. They may receive heat from any number of heavy-industrial users like iron works, chemical manufacturers, and paper mills. Agricultural processors may also supply heat from the agricultural industry that can be used for applications like for heating water, pre-heating water for steam, and space heating [12].

Within the food and beverage industries, heat recovery is common, but not universal. In 2018, 53% of food, beverage, and tobacco manufacturing plants in the United States participated in energy management practices [13]. But most projects were focused on plant-level, a trend that is also reflected in Washington, where only one large processor, Darigold Issaquah, was identified as having an operational heat recovery project, which delivers warm water to a nearby fish hatchery [14]. Two smaller projects were interviewed for this symbiosis project. BetaHatch, which grows meal worms in Cashmere, uses waste heat from a nearby data processor [15]. The Wind River Project in Carson, WA captures heat used to grow greenhouse microgreens [16]. In neighboring states, CHP (combined heat and power) projects used steam generated at coal and natural gas power plants [17] to supply process steam to a variety of food processors involved in milk, onion, and potato industries [18], [19]. In the Netherlands, McCain Foods and Lamb Weston Meijer (a Dutch subsidiary of Lamb Weston) operate heat sharing projects at frozen french fry plants similar to their facilities in Washington [20]. McCain Foods provides a swimming pool with warm water [21] and Lamb Weston Meijer provides heat to a nearby onion processor [22]. While all of these projects could serve as inspirations for future work, this study focuses on using large ag processors as heat sources for other industrial and commercial purposes. In most cases, Washington's agricultural processors are located at the center of communities built around agriculture. These processors are often the largest consumers of heat and one of the best opportunities for a heat-sharing source.

2. Methods

Heat sharing in the United States is currently unusual, so there are limited examples to help create a system for identifying and developing projects. Generally, it is acknowledged that networking is key to successful projects [23], and that characterizing the wants and needs of different companies is an important task. In Europe, where heat sharing is more common, several large studies can be used as models for this approach. One previous study identified opportunities for heat sharing at data centers in Sweden using a 3-tiered study structure that included a high-level system analysis which identified companies and their energy needs, an intermediate analysis that identified synergies and obstacles between industries, and a detailed level analysis that resulted in suggestions to mitigate obstacles and integrate processes between facilities [5]. Each level of the study's approach used different data sources, beginning with general data and eventually incorporating information gained through stakeholder interviews. This work is focused on the preliminary system-level analysis. It uses information about large agricultural processors identified in the facility database, described in the Quantitative Analysis Appendix, and typical unit-level energy consumption to estimate total fuel and electricity demand for different types of agricultural processors in Washington. Unit-level energy demand is shown in Figure A-3.1.

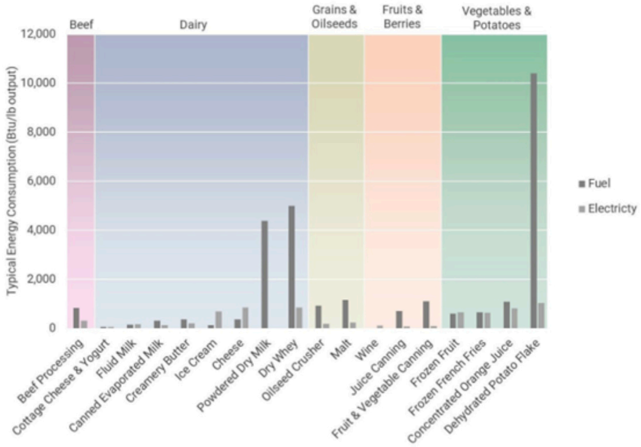

Figure A-3.1: Energy Consumption per unit of output for agricultural processors

The sources used to create the energy consumption estimates are given in Table A-3.1. One of the key functions of packing houses is fruit sorting, which determines whether fruit is suitable for the fresh market or processing. As shown in figure A-3.2, depending on the species, between 81 and 76 percent of fruit is sold fresh [1]. The estimates used general industry values and lack the accuracy of a more detailed study. Process energy efficiency can vary significantly based on a variety of factors including equipment type, age, and plant arrangement.

Table A-3.1: Sources for Energy Consumption at food processors

Group	Process	Source
Beef	Beef	[24]
Dairy	Powdered Skim Milk	[25]
Dairy	Other Dairy	[26]
Grain & Oilseeds	Oilseed Crusher	[27]
Grain & Oilseeds	Malt	[28]
Fruit	Wine	[29]
Fruit	Other Fruit	[30]
Vegetables	Vegetables	[30]

Agricultural processors in Washington are dispersed across many cities, so opportunities for heat sharing are location specific. Projects have previously identified the importance of location for forming relationships between heat sources and heat sinks [23], [31]. Hotmaps, a multi-country project funded by the European Union, maps sources of excess waste heat by volume and temperature [32]. Potential heat sinks are also mapped based on building floor space. This project adapts that approach to include locations that use low-grade heat for industrial and commercial purposes were used as potential heat sinks. These included:

- **Wineries**: Low-grade heat is required for fermentation and aging. Fermentation is a biological process that requires temperatures between 70 and 90F. Aging, which often takes several years, requires consistent temperatures between 50 and 70F [12], [29], [33].
- **Fish hatcheries**: Another biological process that could use low-grade waste heat are fish hatcheries [12].
- **College campuses and hospitals**: Building complexes with large, combined floor spaces are often heated with a central, natural-gas burning heat system. These could be adapted to use heat from agricultural industrial sources [34].

Due to limited data about facility size and temperature, heat demand was not estimated at potential heat sinks. Using information about large agricultural processors (plants with annual inputs of 50,000 tons or more from the facility database and these heat sinks, an intersect analysis was used to determine which processors are within 5 miles of heat sinks, and which types of heat sinks are typically near processors.

3.2 Results

As shown in Figure A-3.2, heat generated at agricultural processors is concentrated among a handful of industries and cities. The cities that generate the most heat include Pasco, Warden, and Moses Lake in the Mid-Columbia Basin. In Pasco the most energy-intensive processor is the Darigold butter and powdered skim milk plant that will begin operation in 2024. Pasco also has a frozen French fry plant and several frozen vegetable processors. In both Warden and Moses Lake, dehydrated potato flake plants consume the most energy. Additionally, each has a frozen French fry plant. And Warden has the state's lone canola crusher and Moses Lake is home to a frozen vegetable plant.

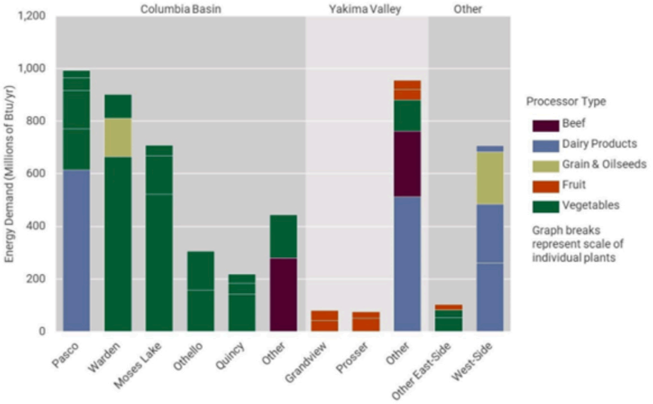

Figure A-3.1: Heat consumption of agricultural processors by location and industry-type

The proximity of large agricultural processors to campus and industrial low-grade heat users is shown in Figure A-3.3. The map shows that not all processors are near any of the 4 types of heat sinks considered, which suggests that although facilities produce excess heat, they may not always have potential customers. The potato and oilseed processors at Warden, the potato fryer at Connell, the beef processor at Wallula, and milk powder plant at Lynden are among the facilities that do not have any intersections with the mapped heat sinks. This is especially significant because the plants included in this list are among the largest agricultural processing energy consumers in the state. Areas with lower overall heat consumption but more intersections with the potential heat sinks include the fruit processors in Yakima, Grandview, and Prosser; the milk processors in Issaquah, Chehalis, and Sunnyside; vegetable processors in Richland, Pasco; and the malt producer in Vancouver.

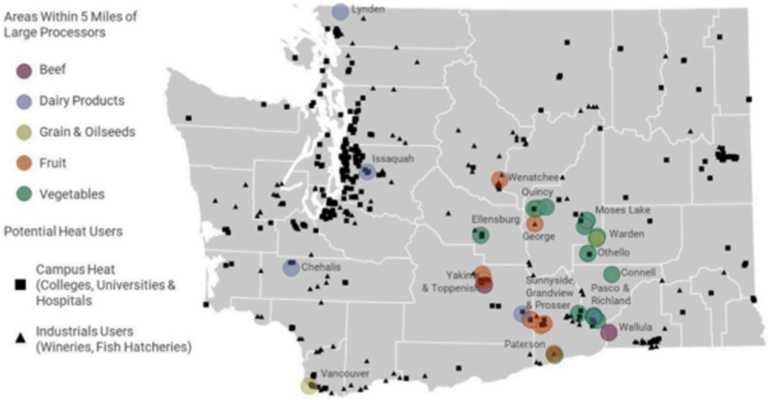

Figure A-3.2 Heat sharing industry intersections

3. Discussion

Barriers to heat sharing include competition for heat, technology limits for heat exchangers, and seasonal variability from both heat sources and sinks. Competition occurs within the source facility [1]as energy recovery is inherently a component of modern industrial design. Steam loops are one of the most common methods used to supply heat throughout facilities [35]. Used steam is returned as warm condensate which requires less energy to heat steam than water. Sharing steam or condensate with other facilities would mean that a greater amount of energy must be consumed at the source facility.

Technology barriers for heat sharing are process specific. Among the process types that account for the most significant energy consumption in Washington, only frozen French fry manufacturers are known to be feasible partners for heat sharing [20], [36]. Technological limitations are the main barrier for other processes as limited information exists for dehydrated potato flake manufacturers and the process used to manufacture skim milk powder is difficult to adapt for energy sharing. For milk powder, significant research has been conducted to improve energy recovery, particularly in spray drying units, but traditional heat exchangers are not a viable option as they cause hot spots which can lead to burned and caramelized milk powder as well as fouled heat exchangers [25], [37], [38].

Depending on the type of feedstock, agricultural processors may operate year-round or for a brief period during the harvest season [7]. In Washington, the most reliable continuous processors are those that are dependent on livestock: milk and beef processors. Crops that store well, like grain, apples, and potatoes allow facilities to operate for most of the year. Other processors typically operate for a few months in the summer or fall. Variations in demand from heat sinks are also seasonally variable. For instance, sinks that require heat near room temperature will require the most heat during the winter, with little to no demand during the summer.

Opportunities to supply heat to the agricultural industry from non-ag sources have significant potential and are worth considering for future studies. Western Washington is home to several facilities that generate large amounts of energy like natural gas energy plants, petroleum refineries, chemical manufacturers, paper mills, and sawmills. Some of these already have CHP projects [39]. Eastern Washington, the location of most agricultural processors, has less heavy industry, but other opportunities may also be applicable. In particular, the Columbia Basin's low electricity rates have attracted data centers [40], which generate heat from computer processing that is removed by heat exchangers. While this is also low-grade heat, several studies have considered its potential applications [5], [41]. An advantage of using heat from data centers is that there are relatively few opportunities to use heat in-facility, so most heat is currently wasted instead of recycled.

References

[1] A. Hilta, A. Djemaa, G. Seck, and G. Guerassimoff, “Assessment of the Potential of Heat Recovery in Food and Drink Industry by the Use of TIMES Model,” 2011.

[2] J. L. Pellegrino, N. Margolis, M. Justiniano, M. Miller, and A. Thedki, “Energy Use, Loss and Opportunities Analysis: U.S. Manufacturing & Mining,” 2004. [Online]. Available: www.eere.energy.gov/industry/energy_systems

[3] “Renewable Industrial Process Heat,” Environmental Protection Agency, 2022. https://www.epa.gov/rhc/renewable-industrial-process-heat (accessed May 25, 2023).

[4] J. Ling-Chin, H. Bao, Z. Ma, W. Taylor, and A. Paul Roskilly, “State-of-the-Art Technologies on Low-Grade Heat Recovery and Utilization in Industry,” in Energy Conversion - Current Technologies and Future Trends, IntechOpen, 2019. doi: 10.5772/intechopen.78701.

[5] J. Lind and E. Rundgren, “Industrial Symbiosis in Heat Recovery Collaborations between Data Centers and District Heating and Cooling Companies,” 2017.

[6] BCS Incorporated, “Waste Heat Recovery: Technology and Opportunities in U.S. Industry,” 2008.

[7] Y. Luo, S. Jagtap, H. Trollman, and G. Garcia-Garcia, “A Framework for Recovering Waste Heat Energy from Food Processing Effluent,” Water (Switzerland), vol. 15, no. 1, Jan. 2023, doi: 10.3390/w15010012.

[8] G. Legorburu and A. D. Smith, “Energy modeling framework for optimizing heat recovery in a seasonal food processing facility,” Appl Energy, vol. 229, pp. 151–162, Nov. 2018, doi: 10.1016/j.apenergy.2018.07.097.

[9] “Use of energy explained: Energy use in industry,” United States Energy Information Administration, 2021. https://www.eia.gov/energyexplained/use-of-energy/industry.php (accessed May 28, 2023).

[10] L. Gast, A. Cabrera Serrenho, and J. M. Allwood, “What Contribution Could Industrial Symbiosis Make to Mitigating Industrial Greenhouse Gas (GHG) Emissions in Bulk Material Production?,” Environ Sci Technol, vol. 56, no. 14, pp. 10269–10278, Jul. 2022, doi: 10.1021/acs.est.2c01753.

[11] F. Huang, J. Zheng, J. M. Baleynaud, and J. Lu, “Heat recovery potentials and technologies in industrial zones,” Journal of the Energy Institute, vol. 90, no. 6. Elsevier B.V., pp. 951–961, Dec. 01, 2017. doi: 10.1016/j.joei.2016.07.012.

[12] T. Parker and A. Kiessling, “Low-grade heat recycling for system synergies between waste heat and food production, a case study at the European Spallation Source,” Energy Sci Eng, vol. 4, no. 2, pp. 153–165, Mar. 2016, doi: 10.1002/ese3.113.

[13] “Table 8.1 Number of Establishments by Participation in General Energy-Management Activities, 2018,” 2018.

[14] “Fact Sheet for Darigold Issaquah: NPDES Permit WA0032034,” 2014.

[15] “Beta Hatch Opens State-of-the-Art Facility to Produce the World’s Most Sustainable Nutrition,” McKinistry, 2022. https://www.mckinstry.com/beta-hatch-opens-state-of-the-art-facility-to-produce-the-worlds-most-sustainable-nutrition/ (accessed May 30, 2023).

[16] “Wind River Circular Systems (The Wind River Project).” https://windriverproject.com/ (accessed May 30, 2023).

[17] “CHP Installations,” United States Department of Energy. https://doe.icfwebservices.com/chp (accessed May 25, 2023).

[18] “Hermiston Generating Plant,” Perennial Power, 2020. http://www.perennialpower.net/Portfolio/Hermiston-Generation-Plant/ (accessed Feb. 27, 2023).

[19] “Air Permit for PGE-Coyote Springs, Permit No. 25-0031-TV-01,” 2019.

[20] K. J. West, J. J. De Jonge, and M. Van Hout, “Decarbonisation Options for the Dutch Potato Processing Industry,” 2021. [Online]. Available: www.pbl.nl/en.

[21] “CêlaVíta’s potatoes heat Wezep’s swimming pool (translated title),” Biind, 2018. https://www.biind.nl/artikel/de-aardappelen-van-celavita-verwarmen-het-zwembad-van-wezep (accessed May 25, 2023).

[22] “Onion Company Uses Residual Heat from Fries Factory,” 2018. Accessed: May 25, 2023. [Online]. Available: https://www.stimular.nl/praktijkvoorbeelden/lamb-weston-meijer-en-wiskerke-onions-restwarmte/

[23] A. Heyes and H. Javed, “Analyzing the technical and economic potential of energy symbiosis,” 2022.

[24] S. Li, R. M. M. Ziara, B. Dvorak, and J. Subbiah, “Assessment of water and energy use at process level in the U.S. beef packing industry: Case study in a typical U.S. large-size plant,” J Food Process Eng, vol. 41, no. 8, Dec. 2018, doi: 10.1111/jfpe.12919.

[25] S. N. Moejes and A. J. B. van Boxtel, “Energy saving potential of emerging technologies in milk powder production,” Trends in Food Science and Technology, vol. 60. Elsevier Ltd, pp. 31–42, Feb. 01, 2017. doi: 10.1016/j.tifs.2016.10.023.

[26] A. Brush, E. Masanet, and E. Worrell, “Energy Efficiency Improvement and Cost Saving Opportunities for the Dairy Processing Industry: An ENERGY STAR ® Guide for Energy and Plant Managers,” 2011.

[27] J. A. Obnamia, H. L. MacLean, and B. A. Saville, “Regional variations in life cycle greenhouse gas emissions of canola-derived jet fuel produced in western Canada,” GCB Bioenergy, vol. 12, no. 10, pp. 818–833, Oct. 2020, doi: 10.1111/gcbb.12735.

[28] “Malt Facts,” The Maltsters’ Association of Great Britain. https://www.ukmalt.com/uk-malting-industry/how-malt-is-made/malt-facts/#:~:text=Energy%20usage%20per%20tonne%20of,to%20produce%20in%20the%20maltings. (accessed May 24, 2023).

[29] M. Malvoni, P. M. Congedo, and D. Laforgia, “Analysis of energy consumption: A case study of an Italian winery,” in Energy Procedia, Elsevier Ltd, Sep. 2017, pp. 227–233. doi: 10.1016/j.egypro.2017.08.144.

[30] E. Masanet, E. Worrell, W. Graus, and C. Galitsky, “Energy Efficiency Improvement and Cost Saving Opportunities for the Fruit and Vegetable Processing Industry An ENERGY STAR ® ® ® ® Guide for Energy and Plant Managers,” 2008.

[31] L. W. Baas and F. A. Boons, “An industrial ecology project in practice: Exploring the boundaries of decision-making levels in regional industrial systems,” J Clean Prod, vol. 12, no. 8–10, pp. 1073–1085, Oct. 2004, doi: 10.1016/j.jclepro.2004.02.005.

[32] “Hotmaps Project,” Hotmaps. https://www.hotmaps-project.eu/ (accessed May 30, 2023).

[33] A. Matarazzo, F. Copani, M. Leanza, A. Carpitano, A. Lo Genco, and G. Nicosia, “The Industrial Symbiosis of Wineries: An Analisys of the Wine Production Chain According to the Preliminary LCA Model.” [Online]. Available: www.intechopen.com

[34] “District Energy Systems Overview,” 2018.

[35] A. McMullan, “Industrial Heat Pumps for Steam and Fuel Savings: A Best Practices Steam Technical Brief,” 2003. [Online]. Available: www.eere.energy.gov

[36] W. Van Loon, “Process Innovation and Quality Aspects of French Fries,” 2005.

[37] T. Rigter, “Valorization of Waste Heat in the Food Industry,” 2020.

[38] M. J. Atkins, M. R. W. Walmsley, and J. R. Neale, “Integrating heat recovery from milk powder spray dryer exhausts in the dairy industry,” Appl Therm Eng, vol. 31, no. 13, pp. 2101–2106, Sep. 2011, doi: 10.1016/j.applthermaleng.2011.03.006.

[39] “Combined Heat and Power Installations in Washington,” U.S. Department of Energy. https://doe.icfwebservices.com/state/chp/WA (accessed Mar. 09, 2023).

[40] J. Glanz, “Data Barns in a Farm Town, Gobbling Power and Flexing Muscle,” New York Times, 2012.

[41] K. Ebrahimi, G. F. Jones, and A. S. Fleischer, “A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities,” Renewable and Sustainable Energy Reviews, vol. 31. Elsevier Ltd, pp. 622–638, 2014. doi: 10.1016/j.rser.2013.12.007.

Appendix B

Overview of Policy Context

1. Introduction

To provide a better high-level understanding of where and how existing policies are shaping the development and implementation of agricultural symbiosis, this appendix summarizes and contextualizes some key elements of the policy landscape. The goal of this review was not to dig into the details of particular regulations, grant programs, or other support. Instead, the goal was to identify major areas in which existing policy related to different technologies are relevant to industrial symbiosis in the agricultural sector.

1.2 Sources of Information

This appendix summarizes a number of different sources. Whether they use the words “industrial symbiosis” or not (and in most cases they did not), stakeholders across Washington have important place-based experience trying to bring industrial symbiosis projects to fruition within the agricultural sector in Washington. While other aspects of their experience relating to opportunities and barriers are summarized in the main report, within this appendix we took a more detailed look at observations and opinions relating to existing and future policy that were expressed during the CSI interviews.

We also drew on several additional, relatively recent (within the 5-7 years) roadmaps and workgroups for Washington and the Pacific Northwest for technologies that are relevant for industrial symbiosis in the agricultural sector, including for renewable natural gas [1], biochar [2], and sustainable aviation fuels [3]. Each of these documents focuses on a specific industrial symbiosis opportunity that may include other sectors of the economy, but each also has an important intersection with the agricultural sector. Given that these efforts incorporated the views of a diverse set of industry, community, and academic experts, these roadmaps were examined to understand the views of a broader group of individuals who have been active in this area over time. Based on these observations, we also reviewed state-level policy in areas that are relevant for agricultural symbiosis projects. Finally, the academic literature relating more generally to industrial symbiosis and policy has been reviewed, with an eye towards how this literature may confirm regional experiences, or bring in new ideas.

1.3 The Economic Context for Industrial Symbiosis

Economic benefits and the ability to meet regulatory requirements are considered to be major motivations sustaining successful industrial symbiosis projects and relationships [4], [5], [6] [7] [8]. At their heart, industrial symbiosis relationships are economic arrangements that can provide services and products. As an example, an on-farm dairy digester with nutrient recovery technologies added may provide specific products such as renewable natural gas or energy, fiber that can be used for animal bedding, and perhaps nutrient-rich amendment products (Figure B-1.1). Products may be utilized on-farm (as replacements for costs that would otherwise be incurred), or sold to other entities. However, they may also provide services, for example water treatment, or (if they accept pre-consumer food wastes from nearby food processors) organic waste treatment.

For both products and services, the farm may realize economic benefits in two forms. The first of these is revenues for products or services sold for others. Thus, in the example above, revenues can come in the form of tipping fees from food processors who are leaving organic wastes to be digested, carbon credits from reducing greenhouse gas emissions, sales of renewable energy, fiber that can be sold to the horticultural industry for inclusion in potting mixes - or a number of other possible products. The mix of products will depend on the capacity of the dairy and the needs of existing markets (which may vary across time or in different locations). The other form of economic benefits is avoided costs. Thus, for example, fiber from a dairy digester can be used as animal bedding,

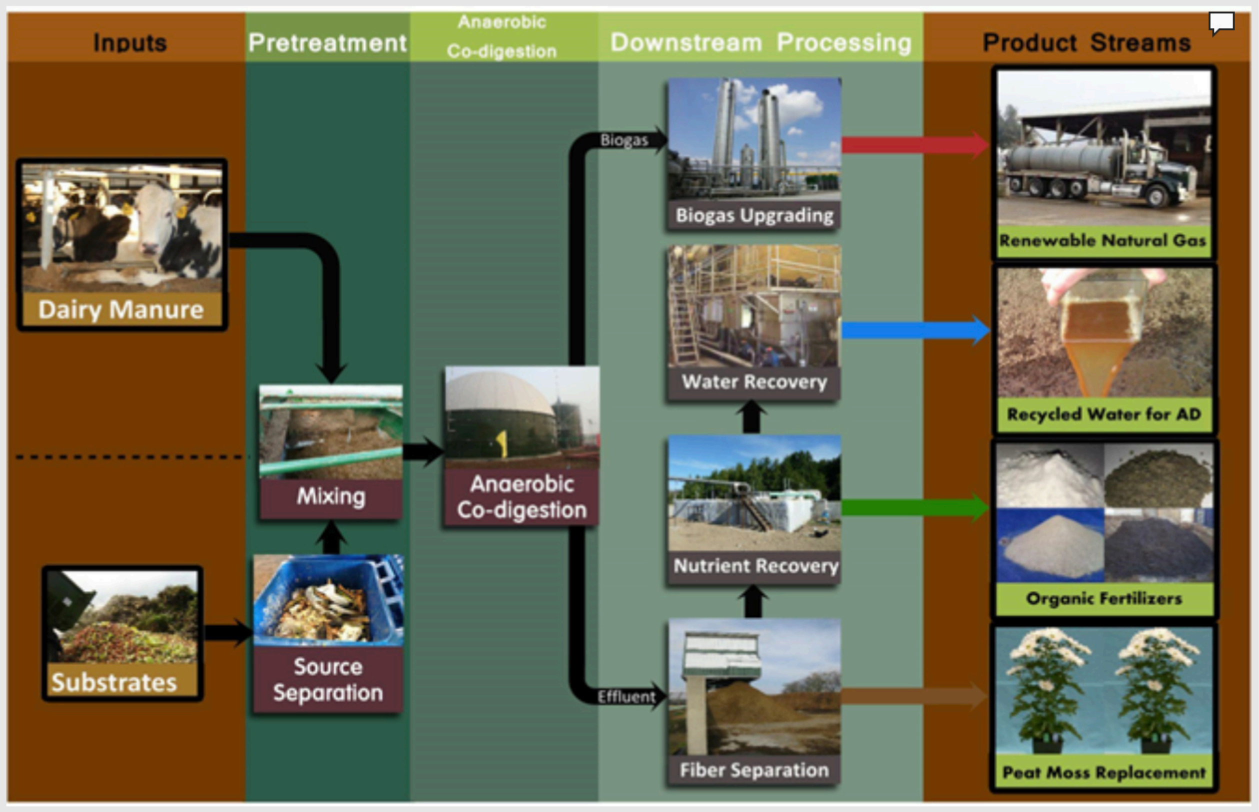

Figure B-1.1: Generalized figure of an on-farm dairy digester that accepts off-farm pre-consumer food wastes and generates several different end-products, including renewable natural gas, recycled water that can be used within the digester, organic fertilizers, and a peat moss replacement. Reproduced with permission from [9].

thus reducing the dairy's bedding purchases. Nutrient recovery systems may reduce the costs that would otherwise be incurred from trucking manure to far-flung fields to ensure that nutrients are applied consistent with plant needs. There may also be benefits which are not directly monetized, for example, reductions in odors and the generation of sustainable jobs that add to the economic base.

Not all industrial symbiosis projects need to be this complex. But stakeholder experience and research both suggest that economics for larger projects usually depend on a combination of revenue sources from energy and non-energy products and services (including in many cases incentives, such as carbon credits or incentives for renewable energy production) to remain viable [1], [10]. There is often the potential to generate both products with lower value but broader markets, and the potential to generate higher value products, which may have smaller overall markets and/or require more specialized knowledge, facilities, and financial and human resources to produce. Neither of these approaches is a "sliver bullet" for ensuring the economic viability of industrial symbiosis, and both may require support for market development.

The other important feature of these systems is that many of them are industrial-scale installations, with relatively high capital costs for equipment that has a long lifetime (one or often multiple decades). As such, stability of economic arrangements may be an important consideration, both for the installing company and for investors and financiers.

The other important implication of the fact that as industrial-scale installations, most will require siting and permitting. Air, water, and solid waste permitting, and other regulatory requirements exist to protect the environment and public health. As such, compliance with existing regulations is an important part of ensuring that these installations are good neighbors to the communities in which they are located - and achieve their desired benefits without creating negative environmental impacts. And yet, siting and compliance with existing permitting requirements may also form an important barrier to industrial symbiosis development, especially for newer technologies that may not be "business as usual" operations [2], [3].

Given this broader economic context, there is potentially a role for policy to play, and it may be most effective when it takes a holistic approach to the barriers faced by these types of operations. The sustainable aviation fuel workgroup update notes from a World Bank report that: "a comprehensive public policy and regulatory framework should define production incentives needed to increase supply and lower costs, while incentivizing sustainable aviation fuel usage [3]. To be effective, high level policy commitments must be accompanied by the development of financing schemes (including guarantees instruments), easement of environmental licensing, and promotion of exports to meet the growing demand."

1.4 Lessons Learned: the economic and other hurdles facing Industrial Symbiosis ventures

Industrial symbiosis ventures are not always successful. The failure rate for new businesses is high. To some extent, this may be merely a reflection of the fact that success is challenging for all new businesses, whatever the type. It also may be because industrial symbiosis ventures run the entire range of size and sophistication: from a few individuals with a great idea working with limited capital, to business ventures by some of the world's largest energy companies.

Therefore, as a counterpoint to the many successful and ongoing agriculture symbiosis projects that were profiled throughout the main report, we also reviewed the gray literature for existing descriptions for agriculture and forestry symbiosis projects that ceased operations over the past few years. This review indicates that economic pressures are among the most commonly cited reasons for abandonment of industrial symbiosis ventures, and given that many symbiosis projects rely on a number of different revenue streams (and sometimes input streams) to achieve economic viability, these economic pressures can come from a number of different sources. A lack of markets (impacting revenues), especially for those that produce new products, can be important (e.g. Columbia Pulp, Starbuck, WA, [11]). Changes in subsidies that impact revenues can also be important, as can rising input or construction costs (e.g. Parkland Corporation, Burnaby, BC, [12]). For dairy digesters, at least one closure of a Washington dairy digester is attributable to the closure of the underlying dairy operation, likely due to ongoing economic pressures and consolidation within the industry [13].

Even for those symbiosis projects that survive, challenges can include navigating substantial volatility in various markets. For example, in the 2010s, on-farm anaerobic digesters in Washington State and elsewhere in the U.S. experienced substantial challenges, with only one of four products having stable prices. Volatility was substantial for carbon credits and renewable energy credits due to regulatory uncertainty, and prices for electricity dropped in the Pacific Northwest and elsewhere in the U.S. as natural gas prices fell [14], [15].

Uncertainty relating to permitting is another important barrier and may result in loss of investment capital, and projects may ultimately either move to more favorable jurisdictions or ultimately collapse. The Sustainable Aviation Biofuels Workgroup [3] highlights increasing national recognition that federal, state, regional, and local permitting processes may delay construction of clean energy projects for several years. On the ground, Washington experienced this when REG and Phillips 66 withdrew their permit application for the Green Apple Renewable, LLC project in Ferndale, WA and REG invested the money by expanding an existing facility in Louisiana [3]. Permitting processes may include opportunities for public engagement, and at times, these public processes can prove challenging (e.g. [16])

Beyond these economic and regulatory reasons projects may fail due to issues with proposed technologies or processes not performing as desired (e.g. Upward Farms, Brooklyn, NY and Wilkes-Barre, PA, [17]; Red Rock Bioenergy, Lakeview, OR, [18]). There have also been at least a few cases over the last decade where failed waste conversion technologies left behind hazardous materials that needed to be cleaned up and required governmental intervention (e.g. Onalaska Wood Energy, Chehalis, WA, [19]).

It may be helpful to think of industrial symbiosis projects as encompassing several distinct steps, or links in a chain between the point where excess heat, water, or biomass is considered “waste”, and its successful recapture and reuse. The focus may sometimes be on one step of the process, but there are often several steps that are needed to achieve successful symbiosis. For biomass recovery, for example, that could include acquiring feedstocks and ensuring it meets minimum quality and purity requirements, a main waste-conversion technology such as a digester, and one or more additional processing technologies that are used to achieve saleable products and services, as well as market-development for each of those products or services. Each of these links needs to be successful for industrial symbiosis projects to experience sustained success.

From a broader perspective, it may also be helpful to see each individual agriculture symbiosis entity existing within an ecosystem of other players. As industrial symbiosis becomes more common, more robust ecosystems may evolve, when there are more players, and thus more opportunities for a particular industrial symbiosis technology to remain economically viable over a longer timeframe. Less robust ecosystems (which may be more frequently the case for emerging technologies) may make it more likely that any given company will not be able to sustain economic viability over the long run.

2. Identified Policy Needs

Detailed analysis of potential policy changes was outside the scope of this proviso, yet the stakeholder engagement process did elicit some general recommendations. Stakeholders interviewed by CSI generally expressed their preference for incentive based policies over additional regulatory policies. However, there was quite a bit of diversity in terms of what types of incentive-based policy were recommended, with suggestions including:

- Continuing and/or expanding existing grant programs that support agricultural symbiosis projects.
- Bolstering offtake markets. In the case, a stakeholder was discussing the particular example of helping create a market for recovery of nutrients like nitrogen and phosphorous in addition to carbon and energy for anaerobic digesters,
- Helping businesses and or local governments engage in research and development and/or the necessary feasibility studies to get agriculture symbiosis started,
- Providing cost share for start up costs for agriculture symbiosis projects, such as purchasing equipment.

It is important to note that there was not necessarily stakeholder agreement about which of these pathways were desirable, nor about the details of how such incentives might be implemented. In reviewing roadmaps and workgroup processes, it was noted that the sustainable aviation biofuels workgroup also had a diversity of opinions regarding specific incentives [3].

Other themes that emerged from the stakeholder interviews included the observation that incentives may not always “tip the balance”, depending on the amount of financial help they provide. One interviewee specifically noted that grant programs requiring a one-to-one match for grant funds can still result in high capital costs for large agricultural symbiosis projects. Several interviewees also noted that creating a program specifically focused on agriculture symbiosis at the state level would help ensure that some portion of funds specifically support symbiosis in the agriculture sector.

Academic literature relating to incentives and technology adoption suggests that a key characteristic of effective incentive-based policy is reducing risk and uncertainty [20], [21], for example by reducing the amount of money that the adopter must invest into a new practice or technology. Offering incentives over time frames that match the technology or practice adoption can be an important aspect of reducing uncertainty. If adoption of technology will require many years to make back the money spent to acquire it, then incentives will be more beneficial if they are spread out over a similar amount of years [21], [22], [23]. Similarly, for industrial symbiosis opportunities that take a number of years to plan and bring to fruition, ensuring that the incentive environment is stable over more than a few years can be helpful to reducing risk [3]. This can lessen the risk that adopters may feel regarding the long-term economic success of a technology they have invested in. One - but certainly not the only - example of these types of longer-term incentives from the bio-energy sector is feed-in-tariffs. These tariffs provide a guaranteed above market price to renewable energy providers, usually with a long-term contract over 15-20 years [20], [23]. Feed-in tariffs were first used in the U.S., but have been used widely around the globe over the last decade, including in Germany, Japan, and China. In the U.S., they may be more commonly used in combination with other policy tools, including rebates for purchasing renewable generation equipment, renewable portfolio standards, net metering, or production- or investment-based tax incentives [24].

Flexibility in incentives can be another important feature, as lack of flexibility has been directly linked to lower adoption levels [21]. Examples include allowing for adoption of various practices or technology which will lead to the same desired benefit [21], or allowing transferability of incentives so that more than just one individual or business could benefit from the incentive [22]. Finally, tailoring incentives to different localities can improve adoption levels [21], [22], by responding to the specific needs of a community and providing more relevant benefits for adopters.

2.1 Support for Development of Emerging Markets

Market development is critical when new products are being developed, and the potential for support for market development was expressed throughout interviews and roadmaps. For example, CSI interviewees noted the need to bolster markets for non-energy products from agricultural symbiosis projects. Meanwhile, recommendations from the RNG road mapping process included “fund[ing] research and development of technological innovations that …build markets for value-added co-products [1].” And the biochar roadmap indicated a need for “near-term research focused on market-development activities [3].” This included, for example, efforts to develop protocols and specifications to ensure product consistency and facilitate appropriate use of biochar. It also included a focus on near-term research and pilot- or larger-scale demonstrations of biochar technology, showing how biochar can generate direct economic value when used to address specific problems (e.g., soil acidity, low water-holding capacity, fire-hazard reduction, mined land reclamation, composting odors and efficiencies, and storm-water filtration) as well as the development of new high-value C-based products and materials (e.g., catalysts, battery electrodes, and reductants for specialty metallurgical operations).

Successful industrial symbiosis projects are sometimes also referred to as “biorefineries”. Similar to oil refineries, these biorefineries integrate a core processing technology with multiple additional downstream processes to generate a number of value-added products including fuels, power, and chemicals. As mentioned above, many projects depend on a combination of revenue sources to remain economically viable. If new, each of these products may benefit from market development. This can include both lower and higher value products (e.g. understanding how biochar applied to soils impacts soil microbial activity over time versus testing of new bioplastics) or services (e.g. working across the American biogas industry to develop a new carbon accounting methodology to measure the carbon intensity of all biogas projects and ensure consistency [25]).

2.2 Institutional support

Alongside this diversity of products, a diversity of types of actions are needed to support market development. In some cases, policy creates, or vastly expands, particular markets (e.g. carbon policy that creates a more robust market for carbon sequestration in the case of biochar, renewable fuel standards or low carbon fuel standards support renewable energy generation). In other cases, applied research is needed to help potential buyers understand and use new biologically-based products that are similar to (but sometimes not the same as) current standard products. In yet other cases, coordinated actions by industry, researchers, and others can help create industry standards that support consumer knowledge about new products they are purchasing For example, research has shown that purchasers of manure-derived nutrient products from dairies value these products differently than the chemical fertilizers they replace, and that information relating to nitrogen release may be one important factor supporting more widespread use [26].

Many longer-standing industrial symbiosis projects in the region - both those in the agricultural sector, and those in other sectors - have evolved over time to generate different end products. This flexibility has helped projects to remain economically viable by responding to changes in incentives and changes in market-driven prices over time. For example, the King County's Cedar Hills Landfill, the first Washington landfill to develop an RNG project in 2009, originally cleaned their landfill gas and sold it for electricity production [1].

Likewise, some of Washington's dairy digesters - some of the oldest agricultural symbiosis projects in the state - show a similar evolution from electricity production sold to the local grid, to other products: either RNG production (most viable at larger scales), or electricity that can be wheeled to California and can receive additional subsidies for producing renewable electricity specifically for charging electric vehicles. These projects have proven viable over time due to state and federal grant programs, PSE's willingness to provide supportive power purchase agreements, value added co-products (e.g., fiber and nutrients), tipping fees for accepting food processing waste, and beneficial tax incentives (e.g., deferred property tax and sales tax exemption).

2.3 Support to Overcome Regulatory Hurdles

As industrial facilities, industrial symbiosis project sites may require permits for air, storm water, waste discharge, solid waste, and conditional use as well as other environmental review. As new facilities engage in processes outside the "business as usual" for which regulation is designed, they often have additional regulatory hurdles that add time and expense to project establishment.

In some cases, state government and other collaborators have come together to reduce regulatory hurdles while ensuring that environmental and public health are adequately protected. One successful strategy implemented for industrial symbiosis in the dairy sector, was the adoption in Washington of a solid waste permit exemption for digesters that are accepting pre-consumer food waste at less than 30% by volume and follow other guidelines to ensure that nutrients are handled appropriately and other potential concerns are addressed [27]. This exemption was established through Legislation passed in 2009 and greatly eased the regulatory burden for on-farm dairy digesters that were digesting mostly manure and wanted to add pre-consumer food wastes. In these digesters, food wastes act synergistically with the manure and can greatly enhance biogas production (and hence project economics), due to the higher energy content of food wastes. In many cases, the project also earns a tipping fee for accepting organic wastes, an added revenue stream that can be an important aspect of project viability [10].

Other regulatory challenges remain to be addressed. For biochar, air quality permitting can be a major barrier, and a variety of potential pollutants should be considered, as air pollutant emissions from biochar production units can vary widely depending on biomass feedstock composition and biochar production system design, operation, and use of add-on control devices [28]. Those who are exploring the use of biochar production systems to replace open burns in forestry and agriculture will generally find that despite a clear air quality benefit, the applicable regulatory process is substantially more complex, costly, and time consuming than the permitting process for open biomass burning [28]. Many, if not most, biochar production systems (even those that are very small scale) will fail to qualify for an exemption from air quality permitting and thus will require a permit from the appropriate agency. Biochar production systems that have the capacity to discharge emissions exceeding a specified threshold may be subject to Title V or New Source Review/Prevention of Significant Deterioration permitting requirements, a more costly and time-consuming process. Meanwhile, data relating to emissions from various commercially available technologies (which are important for guiding decisions throughout the air permitting process) are few [28]. This hampers the process and can greatly increase the cost, because in evaluating emissions rates for new sources, permitting agencies prefer source test performance data from similar units to the one being proposed [28].

Reducing the size of this barrier will likely take sustained action on several fronts, including collection of emissions data for a variety of potential pollutants from a number of the more common technologies. The situation may also benefit from conversations between scientists, industry, and regulators to develop more efficient permitting pathways where this is possible without compromising public health [2], [3], [28].

2.4 Facilitating the Development of Group Knowledge and Experience

The CSI stakeholder interviews indicated substantial interest in bringing people in the field together to exchange ideas and discuss synergies that could lead to successful agriculture symbiosis projects. Improved coordination mechanisms and social networks can benefit industrial symbiosis projects [4], [29], and because industrial symbiosis as a whole often involves partners from different economic sectors, there is an important potential impact of helping potential partners in diverse sectors find each other and explore partnerships via such groups. In addition, bringing together individuals working on similar projects, such as symbiosis projects within agriculture, can be an important strategy to build knowledge and capacity, and thereby reducing risk in a new endeavor. Increasing the awareness and knowledge of incentives is also crucially important. Potential adopters can be ignorant of incentives, both of their existence and the detailed information which are vital to precipitate adoption [21], [22].

Groups of individuals, especially if they bring together relevant individuals from nascent industries, academia, and relevant government agencies, can also act strategically to address some of the regulatory and market barriers previously discussed. As examples, the RNG roadmap identifies an opportunity for state agencies to work to “coordinate development of a voluntary RNG quality standard with natural gas utilities to enhance access to the natural gas pipeline grid [1].”

A recent review of successful and unsuccessful eco-industrial parks in the United States suggests that stakeholder involvement and dedication, community involvement, and regulatory system/agency support are all critical factors for success [8]. This is consistent with others who have discussed the necessity of intentionally nurturing collaborative and information-sharing relationships [30], [31]. And while government backing is not sufficient on its own when firms do not desire to collaborate, direct and indirect government support in a variety of forms can be important and build interest in, and capacity for, industrial symbiosis [7], [8], [32], [33].

Evaluation of whether or not perceived benefits are being achieved is also important and may involve collaboration between industry and non-industry actors, including academic or agency. These efforts can showcase successes, point to areas for improvement, build evidence for monetization of benefits such as carbon, and ensure consistency [1], [2]. Data gaps in terms of impacts are numerous across worldwide industrial symbiosis efforts, and in some cases positive outcomes are assumed to occur. There is an ongoing need for study of whether or not industrial symbiosis is achieving its desired economic, environmental, and social impacts [6], [29], [34].

3. Overview of Relevant Washington Regulatory Policies

Multiple CSI interviewees acknowledged benefits of current policies in place in Washington, at the federal level, and in other states. Specifically, organic waste diversion laws in both California and Washington were cited as creating early progress in reducing the amounts of organic waste being hauled to the landfill and creating opportunities for synergies between businesses. Similarly, state-level clean fuels standards and the federal renewable fuel standard were praised as providing impetus to develop or use renewable natural gas and other fuels with a lower carbon intensity. A number of existing agriculture symbiosis ventures in the state have benefitted from matching funds or other support provided by the Department of Commerce, including via the Clean Energy Fund Programs. Many interviewees also pointed out that incentive based policies such as the existing that leverage tax credits or programs like the Sustainable Farms and Fields grant program that provide financial assistance to farmers and other businesses are easy to navigate and are already helping make agricultural operations more sustainable, as well as supporting markets for soil amendments and other products from agriculture symbiosis projects.

While there were many positive sentiments around current policy, interviewees also noted that it can be very difficult to navigate some existing opportunities, especially those within current federal policy. Both the Inflation Reduction Act (IRA) and Bipartisan Infrastructure Bill were acknowledged as having potential to support agriculture symbiosis but many, though not all, indicated great uncertainty in how businesses or individuals could take advantage of these pieces of legislation. (See also resources such as the Inflation Reduction Act Guidebook [35], and a website that includes guidance and a sortable list of Inflation Reduction Act programs [36].)

Ensuring alignment between state- and local- level policies may also be important, as indicated by some CSI stakeholder interviewees. For example, geographic proximity can be encouraged through local land use planning - though it is important to note that co-location does not on its own necessarily lead to industrial symbiosis, even when this has been identified as a goal [37]. Opportunities to share “waste” biomass (especially for lower value products, and the wet wastes common within agriculture), heat, and water may necessarily rely on partners who are physically near each other to support economic viability [34]. However, other aspects of industrial symbiosis, including recent efforts to decarbonize supply chains, provide a potential opportunity to “de-couple” industrial symbiosis from physical co-location.

A comprehensive review of all areas of state policy that could potentially impact all types of agriculture symbiosis was outside of the scope of this policy scan. However, in this section, we capture recent and major areas of policy that are likely to be relevant. Agriculture symbiosis, and other types of industrial symbiosis, can support the substantial action and commitments that the state has made in these other spaces. These areas of policy also represent opportunities for leveraging impact across state agencies.

3.1 Climate

The Climate Commitment Act. The Climate Commitment Act caps and reduces greenhouse gas (GHG) emissions from Washington's largest emitting sources and industries, with mechanisms that allow businesses to find the most efficient path to lower carbon emissions. This program aims to ensure that Washington achieves a 95% reduction in GHG emissions by 2050.

The Climate Commitment Act works by setting an emissions limit, or cap, and then lowering that cap over time in line with the state's climate goals. Businesses in the state that emit more than 25,000 MT CO2e (metric tons carbon dioxide equivalents) annually are covered under the regulation, and must either 1) reduce their emissions, 2) purchase allowances, which are offered for sale in the quantities allowed by the cap and/or 3) purchase greenhouse gas offsets in regulatory markets. Offsets can account for up to 5% of needed emissions reductions in the first compliance period and 4% in the second period.

While the Climate Commitment Act is often thought of as being primarily regulatory in nature, the implications of this act for agriculture symbiosis, at least in the near term, are largely indirect. Due to provisions in the law, farm and ranch operations will remain largely untouched by the regulatory portions of the Climate Commitment Act. Moreover, food products and food manufacturing will initially be offered "allowances" for their greenhouse gas production at no cost, due to their status as emissions-intensive, trade-exposed industries. The rationale for this is that these industries that release large amounts of greenhouse gas emissions also face significant national or global competition for their products; thus if faced with sudden, substantial changes to their operations, they could limit operations, close, or transfer production elsewhere - thus failing to achieve worldwide emissions reductions and causing harm to the state's economy.

In effect, what this means is that the regulatory portions of the Climate Commitment Act will likely have less direct impact on the food and agriculture sector in the near term with the primary impact being the potential to voluntarily offer offsets to entities in other sectors which are regulated. Among the four types of offset projects currently adopted under the Climate Commitment Act, Livestock Projects offer an opportunity for agricultural industrial symbiosis. Under this protocol, dairy cattle and swine operations can develop carbon offset projects by installing biogas control systems in the manure management process. Producers can be paid for destroying, using, or selling the methane captured by digesters.

Meanwhile, a second potential opportunity relating to the climate commitment act may come as a result of the revenue generated in the state's cap-and-invest program. Through this program, the revenues generated when regulated entities purchase allowances will be invested in climate projects in the state and will be used to increase climate resiliency, fund alternative-transportation grant programs, and help Washington transition to a low-carbon economy. There are three primary accounts which revenue will fund. 1) The Carbon Emissions Reduction Account is set for projects that reduce emissions from the transportation industry and increase access to public and alternative transportation; 2) The Climate Investment Account will support projects that focus on transitioning to clean energy, ecosystem resilience, and carbon sequestration; and 3) The Air Quality & Health Disparities Improvement Account will support projects that help identify and reduce criteria pollutants and health disparities in overburdened communities highly impacted by air pollution.

3.2 Fuels

Washington Clean Fuel Standard. The Washington Clean Fuel Standard (CFS) was launched on January 1, 2023 after the Washington State legislature initially passed the CFS into law in 2021. The CFS requires the transportation industry (Washington's largest source of greenhouse gas emissions) to reduce the carbon intensity of their fuels or invest in the production of cleaner fuels (such as electricity and low-carbon fuels). The CFS stipulates that the carbon intensity of transportation fuels is reduced by 20% below 2017 levels by 2034. Credits will be given to fleets of vehicles and equipment that use clean fuels, and these credits are traded on an open market. Meanwhile, regulated entities who produce or import high emission fuels like petroleum will be required to purchase credits from this market if they do not sufficiently reduce emissions. The policy aims to support rural economic development and could create opportunities for those within the agricultural sector as demand for biofuels will increase. This policy is modeled after similar programs in California and Oregon and will be compatible with those same programs so that fuels can be traded across state lines and essentially create a regional market for low-carbon fuels.

The Clean Fuel Standard has an advisory panel for agriculture and forestry carbon capture and sequestration. This group offers ideas about how to provide incentives and allocate credits to sequester greenhouse gases related to the Clean Fuel Standard through activities on agricultural and forest lands in Washington.

3.2 Renewable/Clean Energy

Clean Energy Transformation Act (CETA). Enacted in 2019, CETA sets goals for transitioning the state to a carbon-neutral economy by 2030 and achieving 100% clean electricity by 2045. The act includes both regulations and incentives that will create opportunities in the areas of renewable energy generation (installation of wind and solar and production of biogas from anaerobic digestion) and promoting more sustainable agricultural practices (e.g., carbon sequestration).

Washington Renewable Portfolio Standard (RPS) for Electricity. Established by passage of the Energy Independence Act (I-937) in 2006, the Act requires the state's largest utilities to acquire both cost-effective energy efficiency and new renewable energy sources. These sources include wind, solar, and geothermal energy; biogas from landfills, sewage treatment, and animal manure; wave, ocean, or tidal power; biodiesel; and some forms of hydro and biomass energy. Certain technologies that fall under agricultural symbiosis, such as anaerobic digesters, are specifically mentioned as the Act underscores the benefit of small-scale distribution generation systems (five megawatts or less) and provides a double credit toward a utility's renewable energy obligations for using such systems. This Act helped drive development of digesters during the early years of compliance, but more recently RPS compliance requirements have been met by most electrical utilities and thus the interest in anaerobic digesters for power generation has plateaued.

3.3 Organics Management

2022 Organics Management Law. In 2022, Washington's Legislature passed House Bill 1799 (HB 1799) requiring diversion of organic materials away from landfill disposal and towards food rescue programs (preferred for edible food) and organics management facilities. Many aspects of this law focus on post-consumer aspects of the food system (and thus is beyond the scope of agriculture symbiosis as defined for purposes of this report). However, the business requirements and non-residential aspects of the law have the potential to impact agriculture symbiosis directly. And beyond this, the changes induced by the Organics Management Law may also to create opportunities for partnership with agriculture symbiosis projects. Though the bill is complex, some major portions include a study of the adequacy of funding for local government solid waste management, a phased approach to collecting source-separated organics from businesses, the establishment of a Food Center to coordinate statewide food waste reduction, development of a system for voluntary tracking of food donations, model ordinances that address solid waste collection and disposal and discourage disposal of organic materials in landfills, a future requirement that new and updated local comprehensive solid waste management plans must address a new requirement to provide organic materials collection and management to residential and nonresidential customers, and requirements for larger cities and counties to adopt compost procurement ordinances and report tons of organic materials diverted from the landfill.

As local jurisdictions and businesses begin recovering additional post-consumer wastes, an opportunity may exist to partner with facilities that accept agricultural or food processing wastes. This may include opportunities to create low-carbon energy such as renewable natural gas or liquid fuels. Local jurisdictions could consider collaborating with nearby industrial facilities to promote symbiosis opportunities. These collaborations can ensure these renewable energy facilities can obtain the feedstock necessary to create low-carbon fuels.

3.4 Water

Reclaimed Water Rule. Passed in 2018, the State provided guidance for how reclaimed water can be used for irrigation, industrial, augmentation, and other beneficial uses. This rule outlines a framework for permitting and distribution and gives specific guidelines for areas where reclaimed water may be included in the agricultural symbiosis process. (Chapter 173-219 WAC).

WA Stormwater Permitting. Washington issues permits under federal and state laws to control surface and groundwater pollution from runoff. The most-populated cities and counties, as well as industrial sites, construction sites, and many businesses (including many agricultural businesses) have stormwater permits. Additional clarity on policies related to stormwater management and water reuse and where they intersect to support or create barriers against agricultural symbiosis could provide valuable information for reducing policy-based barriers in the water sector.

Voluntary Clean Water Guidance for Agriculture. WA established the Voluntary Clean Water Guidance for Agriculture Advisory Group to advise Ecology on the identification and implementation of practices that support healthy farms and help farmers to meet clean water standards. The guidance resulting from this process generates technical resources to help the agricultural community implement practices in a way that ensures protection of water quality. Including groups that understand the variety of water uses and water-related issues could be beneficial towards supporting improved communication and collaboration across sectors towards new symbiosis projects.

4. Overview of Relevant Washington State Incentive Programs

4.1 Climate

Climate Commitment Act. The incentive-based portions of the Climate Commitment Act (including the climate investment funds and the opportunity to voluntarily offer climate offsets) are described above.

4.2 Soil Health / Climate

Sustainable Farms and Fields Grant Program. The Sustainable Farms and Fields program was created in 2020 by the Washington State Legislature to make it easier and more affordable for farmers and ranchers to implement climate-smart practices and projects that increase carbon sequestration and reduce GHG emissions. Funding is open to conservation districts and other public entities (state agencies, universities, tribes, counties, municipalities, special purpose districts) that possess expertise and can provide technical assistance and capacity to implement climate-smart practices. Examples of potential grant-eligible activities include: developing climate-smart farm plans, cost sharing of climate-smart practices (e.g., tree planting, manure management and storage, planting cover crops, composting, purchasing precision agriculture equipment/technology, etc.), purchasing seed, spores, animal feed, and soil amendments, and purchasing shared-use equipment that will be made available through local entities such as conservation districts or farm co-ops.

4.3 Fuels

Alternative Fuel Commercial Vehicle Tax Credit. This tax credit, which was first signed into law in 2015, has been extended through December 31, 2026, and provides a credit to businesses and individuals who purchase or lease new vehicles that use alternative fuels. The credit is available for up to 50% of the incremental cost of a qualifying vehicle, with a maximum credit of $32,000 per vehicle. It is also available to cover the cost of converting a conventional vehicle to run on alternative fuel, up to a maximum of $16,000 per vehicle. The alternative fuels that are eligible for the credit include compressed natural gas, liquefied natural gas, liquefied petroleum gas, hydrogen, electricity, and biodiesel. This policy could have important indirect impacts on agricultural symbiosis by improving markets for alternative fuels, some of which may be produced through agricultural symbiosis projects.

Alternative Fuel Vehicle Retail Sales and Use Tax Exemption. Sale or lease of new or used passenger vehicles, medium-duty passenger vehicles, and light-duty trucks alternative fuel vehicles (AFV)s is exempt from state retail sales and use tax. Eligible AFVs include those powered by natural gas, propane, hydrogen, or electricity. New vehicles cannot be valued over $45,000 and used vehicles over $30,000 to be eligible.

4.4 Renewable/Clean Energy

Retail Tax Deferral Program for Some Clean Technology Investment Projects. HB 1988 created a retail tax deferral program for some clean technology investment projects, including the manufacturing of such, production of alternative fuels and renewable energy storage. This is meant to provide businesses with the ability to delay their use and sales taxes. They still have to pay them, but if they comply with the requirements they can postpone them. Although some deferral programs can be repaid partially. The bill also includes a pause in sales tax for installing, constructing, repairing or improving electric vehicles, until July 1, 2025.

Renewable Energy System Incentive Program. Originally began in 2005 for homeowners, businesses, and local governments that installed solar, wind, and anaerobic digester systems and was updated in 2019. As of 2021, all funds have been appropriated but it is still technically an active program. Specifically relating to agricultural symbiosis opportunities, as of 2021, the REISP program offers a biogas production incentive of $0.12 and $0.02 per kilowatt-hour (kWh) of electricity generated from biogas produced by an anaerobic digester for residential and commercial scale systems, respectively. The incentive is capped at $5,000 and $25,000 per year for residential and commercial scale systems, respectively.

The Clean Energy Fund Programs. The Clean Energy Fund (CEF) program has funded the development, demonstration and deployment of clean energy technology since 2013. Since its founding, over $144 million has been invested in capital programs to advance projects. Aspects of this fund that are particularly relevant to agricultural industrial symbiosis include the Rural Clean Energy Innovation Fund ($4.6 million in early 2023) and the Research, Development, and Demonstration Program ($8.5 million in 2022). The Forest Products Financial Assistance Program, which requires a match, is a distinct program that may also be of interest to agricultural symbiosis efforts, including biochar.

- **Rural Clean Energy Fund**: $1.8 million is available for projects “that enhance the viability of dairy digesters;” $1.8 million is available to support rural communities in advancing innovative clean energy projects; a minimum of $921,500 is available for tribal projects that advance dairy digester or rural clean energy innovation projects. Applications are due March 23, 2023
- **Research, Development, and Demonstration Program**: “The Research Development and Demonstration program supports projects that engage in strategic research and development for new and emerging clean energy technologies that will help achieve state, national and international climate goals. Grants will be used to match federal or other non-state funds.”
- **Forest Products Financial Assistance Program**: “This program supports the development and expansion of forestry and agroforestry product industries in the State of Washington. This program has an emphasis on use of woody biomass, including by-products of forestry management activities and wood products manufacturing. Proposed projects may utilize biomass to provide thermal energy, electrical energy, or engineered fuel products, or result in energy efficiency improvements. Additional program goals include enhancing forest ecosystem function, reducing forest fire hazards, and supporting resiliency of rural, timber-dependent communities.”

4.5 Water

Water Quality Combined Funding Program. This is an integrated funding program through the Department of Ecology for projects that improve and protect water quality throughout the state. The program combines grants and loans from state and federal funding sources, such as the Infrastructure Act to create high-priority clean water projects across the state. Projects that address standing wastewater, stormwater, and non-point source pollution issues in waterways across Washington State are sought in particular. The extent to which this program is leveraged by existing agricultural symbiosis projects, or could be articulated to explicitly support such, could be valuable.

Stormwater Facility Credits. Properties that have a fully functioning, well-maintained stormwater system are eligible to save money on annual drainage fees. For example, Seattle Public Utilities (SPU) developed the Stormwater Facility Credit Program “to recognize privately-owned systems that reduce stormwater flow and/or provide water quality treatment, which help lessen the impact to the City's stormwater system, creeks, lakes, or Puget Sound.” Working with organizations that have already been leveraging these incentives to understand how credits to achieve novel or symbiotic management goals could benefit towards better aligning water reuse policies for reduced barriers to agricultural symbiosis.

References

[1] J. Jensen, "Harnessing Renewable Natural Gas for Low-Carbon Fuel: A Roadmap for Washington State." Washington State University Energy Program, 2017. https://www.commerce.wa.gov/wp-content/uploads/2018/02/Energy-RNG-Roadmap-for-Washington-Jan-2018.pdf (accessed June 4, 2023).

[2] J.E. Amonette, J.G. Archuleta, M.R. Fuchs, K.M. Hills, G.G. Yorgey, G. Flora, J. Hunt, H.-S. Han, B.T. Jobson, T. Miles, D.S. Page-Dumroese, S. Thompson, K. Trippe, K. Wilson, R. Baltar, K. Carloni, C. Christoforou, D.G. Collins, J. Dooley, D. Drinkard, M. Garcia-Perez, G. Glass, K. Hoffman Krull, M. Kauffman, D.A. Laird, W. Lei, J. Miedema, J. O'Donnell, A. Kiser, B. Pecha, C. Rodriguez-Franco, G.E. Scheve, C. Sprenger, and E. Wheeler, "Biomass to Biochar: Maximizing the Carbon Value." Center for Sustaining Agriculture and Natural Resources, Washington State University, 2021. csanr.wsu.edu/biomass2biochar (accessed June 23, 2023).

[3] Sustainable Aviation Biofuels Workgroup, "Sustainable Aviation Fuels Updates and Recommendations (Opportunities for Washington). December 2022 Final Report." Washington State University, 2022. https://app.leg.wa.gov/ReportsToTheLegislature/Home/GetPDF?fileName=2022-12-01%20SABWG%20REPORT_9cd2afd3-8606-46d2-aa90-42b98fe62972.pdf (accessed June 4, 2023).

[4] M.R. Chertow, "Uncovering" industrial symbiosis," J Indust Ecol, vol. 11(1), pp. 11-30, 2007.

[5] A. Bain, M. Shenoy, W. Ashton, and M. Chertow, "Industrial symbiosis and waste recovery in an Indian industrial area." Resour Conserv Recycl, vol. 54 (12), pp. 1278-1287, 2010. doi: 10.1016/j.resconrec.2010.04.007.

[6] S. Lehtoranta, A. Nissinen, T. Mattila, and M. Melanen, "Industrial symbiosis and the policy instruments of sustainable consumption and production," J Clean Prod, vol. 19(16), pp 1865-1875, 2011. doi: 10.1016/j.jclepro.2011.04.002.

[7] E. Susur, A. Hidalgo, and D. Chiaroni, "A strategic niche management perspective on transitions to eco-industrial park development: A systematic review of case studies," Resour Conserv Recycl, vol. 140, pp.338-359, 2019.

[8] D.V. Perrucci, C.B. Aktaş, J. Sorentino, H. Akanbi, and J. Curabba, "A review of international eco-industrial parks for implementation success in the United States," City and Envt Interac, vol. 16, 100086, 2022. doi: 10.1016/j.cacint.2022.100086.

[9] G. Yorgey, C. Frear, N. Kennedy, and C. Kruger, "The dairy manure biorefinery," Washington State University Extension Publication FS316E, 2019. https://pubs.extension.wsu.edu/the-dairy-manure-biorefinery-anaerobic-digestion-systems-series (accessed June 22, 2023)

[10] Bishop, C., and C.R. Shumway, "The economics of dairy anaerobic digestion with co-product marketing," Rev Agr Econ, vol. 31(3), pp. 394-410, 2009.

[11] "Columbia Pulp has idled its straw pulp facility in Washington State," Paper Industry Technical Association, Feb 24, 2022. https://www.pita.org.uk/what-we-do/news-services/829-columbia-pulp-has-idled-its-straw-pulp-facility-in-washington-state (accessed June 16, 2023).

[12] Lee-Young, J, "What is renewable diesel? Parkland's planned expansion in B.C. scrapped after Biden's U.S. green subsidies," Calgary-Herald, March 6, 2023. What is renewable diesel? Parkland's planned expansion in B.C. scrapped after Biden's U.S. green subsidies | Calgary Herald (accessed June 22, 2023).

[13] personal communication (email), Moulton, P. Washington Department of Commerce, retired. March 23, 2023.

[14] B. Coppedge, G. Coppedge, D. Evans, J. Jensen, E. Kanoa, K. Scanlan, B. Scanlan, P. Weisberg, and C. Frear, "Renewable Natural Gas and Nutrient Recovery Feasibility for Deruyter Dairy," Washington State Department of Commerce, 2012.

[15] N.P. Kennedy, G.G. Yorgey, C.S. Frear, and C.E. Kruger, "On-farm co-digestion of dairy manure with high energy organics," Washington State University Extension Publication FS172E, 2015. https://pubs.extension.wsu.edu/onfarm-codigestion-of-dairy-manure-with-highenergy-organics-anaerobic-digestion-systems-series (accessed May 31).

[16] E. Pearce, "EL opposes plans for biodiesel plant in Pullman," Daily News, March 3, 2023. https://dnews.com/local/sel-opposes-plans-for-biodiesel-plant-in-pullman/article_503f7c01-e63a-586d-997d-deb762bd96c3.html (accessed June 22, 2023).

[17] "Firm building vertical farm in Pennsylvania shuts down," Bay Journal, May 31, 2023. https://www.bayjournal.com/news/pollution/firm-building-vertical-farm-in-pennsylvania-shuts-down/article_84000daa-f8db-11ed-baf6-9f66012a2594.html (accessed June 4, 2023).

[18] Sickinger, T, "Never-opened $300 million-plus biofuels refinery facing foreclosure in southern Oregon," The Oregonian/Oregon Live, January 07, 2023. Never-opened $300 million-plus biofuels refinery facing foreclosure in southern Oregon - oregonlive.com (accessed June 22, 2023).

[19] Yaw, C, "Once-Celebrated Onalaska Company Leaves Behind 100,000 Gallons of Hazardous Waste," The Chronicle. June 16, 2021. https://www.chronline.com/stories/once-celebrated-onalaska-company-leaves-behind-100000-gallons-of-hazardous-waste,267756 (accessed June 22, 2023).

[20] G. Aquila, E. de Oliveira Pamplona, A.R. de Queiroz, P.R. Junior, and M.N. Fonseca, "An overview of incentive policies for the expansion of renewable energy generation in electricity power systems and the Brazilian experience," Ren Sust En Rev, vol. 70, pp. 1090-1098, 2017.

[21] V. Piñeiro, J. Arias, J. Dürr, P. Elverdin, A.M. Ibáñez, A Kinengyere, A., ... and Torero, M, "A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes." Nat Sust, vol. 3(10), pp. 809-820, 2020.

[22] O.A. Olubunmi, P.B. Xia, and M. Skitmore, "Green building incentives: A review," Ren Sust En Rev, vol. 59, pp. 1611-1621, 2016.

[23] W.V. Reid, M.K. Ali, and C.B. Field, "The future of bioenergy," Glob Change Biol, vol. 26(1), pp. 274-286, 2020.

[24] US Energy Information Administration, "Feed-in tariff: A policy tool encouraging deployment of renewable electricity technologies," U.S. Energy Information Administration. May 30, 2013. https://www.eia.gov/todayinenergy/detail.php?id=11471. (accessed April 15, 2023).

[25] Buisnesswire. “Improved Carbon Accounting for Biogas Projects Underway,” Businesswire, may 11, 2023. https://www.businesswire.com/news/home/20230511005795/en/Improved-Carbon-Accounting-for-Biogas-Projects-Underway (accessed June 22).

[26] K. Hills, G. Yorgey, and J. Cook, “Demand for bio-based fertilizers from dairy manure in Washington State: A small-scale discrete choice experiment,” Ren Agr Food Sys, pp. 1-8, 2020. doi: 10.1017/S174217052000023X.

[27] G.G. Yorgey, C.E. Kruger, K. Steward, C.S. Frear, and N. Mena, “Anaerobic co-digestion on dairies in Washington State: The solid waste handling permit exemption,” Washington State University Extension Fact Sheet FS040E, 2011. https://pubs.extension.wsu.edu/anaerobic-codigestion-on-dairies-in-washington-state-the-solid-waste-handling-permit-exemption-anaerobic-digestion-systems-series (accessed June 23, 2023).

[28] B Springsteen, G Yorgey, G Glass, and C Christoforou. 2021. Air Pollutant Emissions and Air Emissions Permitting for Biochar Production Systems. Chapter 12 in J.E. Amonette, J.G. Archuleta, M.R. Fuchs, K.M. Hills, G.G. Yorgey, G. Flora, J. Hunt, H.-S. Han, B.T. Jobson, T. Miles, D.S. Page-Dumroese, S. Thompson, K. Trippe, K. Wilson, R. Baltar, K. Carloni, C. Christoforou, D.G. Collins, J. Dooley, D. Drinkard, M. Garcia-Perez, G. Glass, K. Hoffman Krull, M. Kauffman, D.A. Laird, W. Lei, J. Miedema, J. O’Donnell, A. Kiser, B. Pecha, C. Rodriguez-Franco, G.E. Scheve, C. Sprenger, and E. Wheeler, “Biomass to Biochar: Maximizing the Carbon Value.” Center for Sustaining Agriculture and Natural Resources, Washington State University, 2021. csanr.wsu.edu/biomass2biochar (accessed June 23, 2023).

[29] B. Huang, G. Yong, J. Zhao, T. Domenech, Z. Liu, S.F. Chiu, W. McDowall, R. Bleischwitz, J. Liu, Y. Yao, “Review of the development of China's Eco-industrial Park standard system,” Resour Conserv Recycl, vol. 140, pp. 137-144, 2019. doi:10.1016/j.resconrec.2018.09.013.

[30] D. Gibbs, “Trust and Networking in Inter-firm relations: the Case of Eco-Industrial Development,” Local Econ, vol. 18 (3), pp. 222-236, 2003. doi:10.1080/0269094032000114595.

[31] P. Xiang, and T. Yuan, “A collaboration-driven mode for improving sustainable cooperation in smart industrial parks,” Resour Conserv Recycl, vol. 141, pp. 273-283, 2019. doi:10.1016/j.resconrec.2018.10.037.

[32] M.C.S. de Abreu, and D. Ceglia, “On the implementation of a circular economy: The role of institutional capacity-building through industrial symbiosis,” Resour Conserv Recycl, vol. 138, pp. 99-109, 2018. doi:10.1016/j.resconrec.2018.07.001.

[33] L. Mortensen and L. Kørnøv, “Critical factors for industrial symbiosis emergence process,” J Clean Prod, vol. 212, pp. 56-69, 2019. doi:10.1016/j.jclepro.2018.11.222.

[34] T. Domenech, R. Bleischwitz, A. Doranova, D. Panayotopoulos, L. Roman, “Mapping Industrial Symbiosis Development in Europe: typologies of networks, characteristics, performance and contribution to the Circular Economy, Resour Conserv Recycl, vol. 141, pp. 76-98, 2019.

[35] The White House, “Building A Clean Energy Economy: A Guidebook to the Inflation Reduction Act’s Investments in Clean Energy and Climate Action, Version 2,” The White House, January 2023. Inflation-Reduction-Act-Guidebook.pdf (whitehouse.gov) (accessed June 22, 2023).

[36] America is All In, Federal Climate Funding Hub, 2023. Americaisallin.com (accessed June 22, 2023).

[37] D. Gibbs, and P. Deutz, “Reflections on implementing industrial ecology through eco-industrial park development,” J Clean Prod, vol. 15(17), pp. 1683-1695, 2007. doi:10.1016/j.jclepro.2007.02.003.

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, larvae-based composting, and vermifiltration. 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 CO_2 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 gasses 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 ad- and absorbs 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 CO_2 and 25% in CH_4.

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 NO_x. 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 (CO_2) is released under aerobic conditions, while CH_4 (methane), H_2S (hydrogen sulfide), and N_2O (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 C-1.1: Summary of advantages and disadvantages of different technologies for the valorization of agricultural waste.

	Advantages	Disadvantages
Gasification	• Converts biomass into more concentrated forms of potential energy • 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.	• Biomass entering the system must be as dry as possible to maximize overall efficiency of the process. • Uniformity of particulates is highly important to temperature propagation rates. • Pelletization, grinding, or blending, is necessary for some feedstocks prior to use in thermochemical conversion. • Feedstocks must be free of contaminants that can cause the thermochemical system to clog or render the operation ineffective by reducing peak temperatures. • 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.
Pyrolysis	• The main product of slow pyrolysis, biochar, is an appealing product for use in industrial and agricultural contexts because it readily ad-and absorbs chemical compounds. • Biochar shows promise as a means for carbon sequestration. • Use of biochar in agriculture has many benefits, including improved biomass productivity, decreased irrigation costs, and drawdown of atmospheric carbon dioxide. • Fast pyrolysis produces a bio-oil upon suitable upgrading that may be applied to engines or turbines or used as a refinery feedstock.	• Energy consumption is particularly significant if using wet feedstock. • Dewatering feedstocks before pyrolysis helps to reduce energy consumption. • The oxygen-rich bio-oil is unstable and acidic. Adding catalysts and hydrogen can remedy this problem. • Adding a catalyst adds costs and an additional need to understand maintenance, and replacement cycles.
Anaerobic digestion	• Can process biomass sources with high moisture contents (less than 40% dry matter), contrary to many other waste conversion methods • Generates biogas, which can be used to generate heat and power or upon separations and cleaning renewable natural gas. • The nitrogen-rich slurry (digestate) can be used as a fertilizer. • Little energy demand for heating and electricity. • High energy-efficient process. • Little space requirements. • Low costs. • Odor reduction. • Air quality improvement. • Greenhouse gas emissions reduction. • Reduction in potential pathogens.	• Controlled conditions and careful management for optimization of biogas production. • Biogas may require clean-up prior to use. • Biogas needs to be cleaned-up, concentrated, and compressed to make pipeline quality renewable natural gas

Hydrothermal liquefaction	• Can treat wet wastes without drying by maintaining a liquid water processing medium. • Biocrude can be upgraded to the whole distillate range of drop-in fuel products. • High lipid concentrations are not required for effective HTL energy conversion • The need for energy-intensive feedstock drying is potentially reduced or eliminated because a feedstock slurry is used as an input. • 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. • 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.	• Some aspects of the technology are still at R&D level. • No large-scale, reliable operation hydrothermal liquefaction plant exists in Washington State yet.
Composting	• Compost improves soil conditions. • Replaces the use of chemical fertilizers.	• Organic carbon is lost as carbon dioxide rather than being collected as methane. • Production of compost often causes odor and greenhouse gas emissions.
Vermicomposting	• Improves soil conditions. • Replaces the use of chemical fertilizers.	• 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. • 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.
Larvae-based composting	• Improves soil conditions. • Replaces the use of chemical fertilizers.	• Treatment system size • Need for customized infrastructure to allow raw manure to be conveyed to the black soldier fly beds as soon as possible • Cost of heating the beds
Vermifiltration	• Treats the liquid waste stream from manure systems by reducing and removing dissolved constituents via bacterial degradation. • Improves soil conditions. • Replaces the use of chemical fertilizers.	• Challenges associated with caring for the worms • Difficulties in identifying secondary product markets that produce an appropriate return of investment.

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/m³) and siloxanes (0–40 mg/m³). 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 C-1.2: Characteristics of biogas produced from different source pathways [42].

Sources	**Biogas characteristics**
Landfills	CH_4, CO_2, H_2S, water vapor, other sulfides and mercaptans, siloxane, non-methane organic compounds, oxygen, nitrogen, ammonia, and other trace gases
Wastewater treatment plants	CH_4, CO_2, H_2S, water vapor, siloxanes, and possibly traces of nitrogen and ammonia
Dairy manure	CH_4, CO_2, H_2S, and water vapor
Food processing byproducts	CH_4, CO_2, H_2S, and water vapor
Municipal organic waste	CH_4, CO_2, H_2S, water vapor, siloxanes, other gases in trace amounts

- **Hydrogen sulfide (H_2S)**: 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 H_2S and CO_2 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 H_2S and CO_2 in water as compared to CH_4. For instance, CO_2 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 CO_2 and CH_4 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 CO_2 produces 1 mol of oxygen, which affects the quality of the final product.

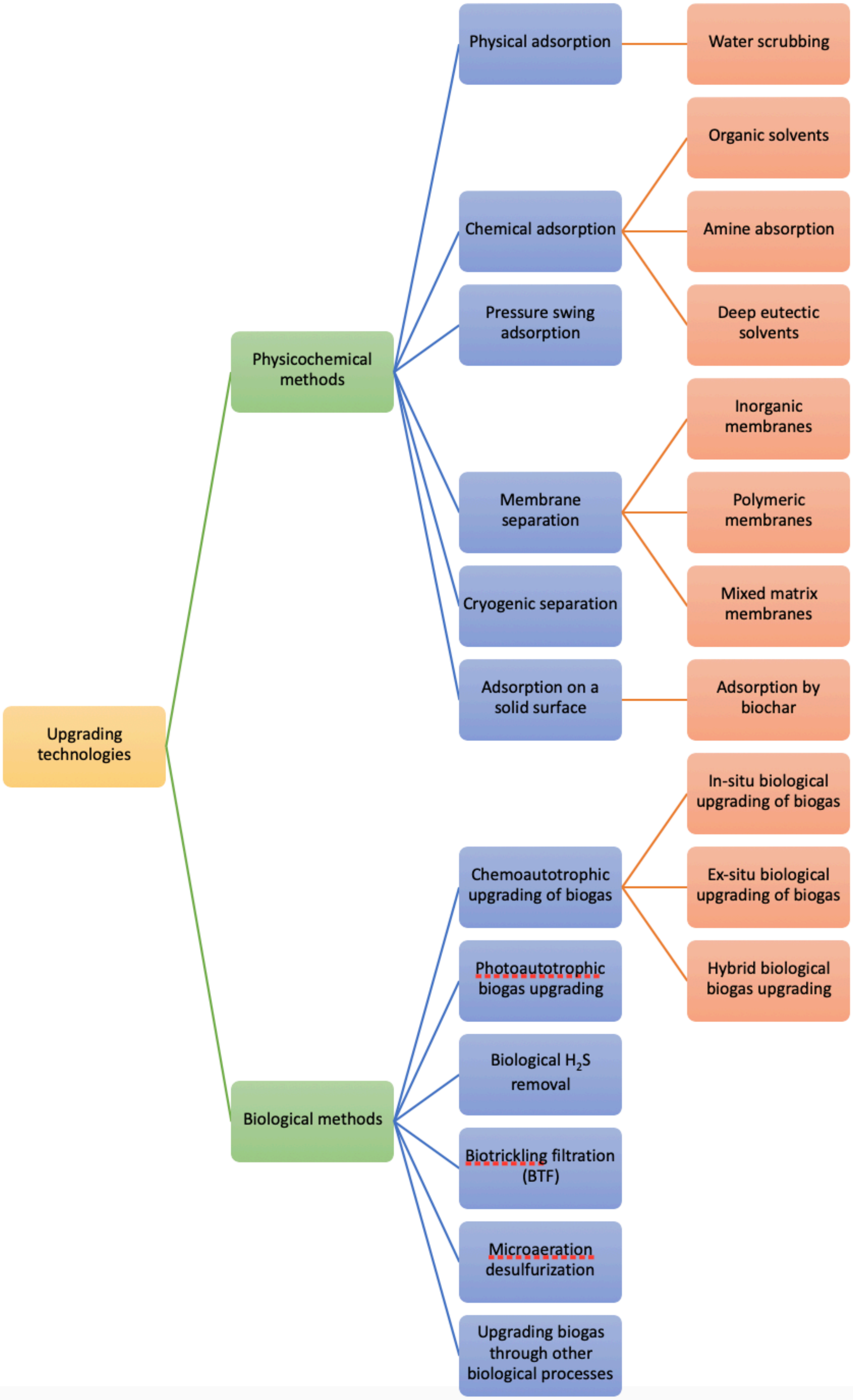

Figure C-1.1: Upgrading technologies for the production of Renewable Natural Gas from biogas.

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.

Facility	Type	RNG [MMBtu/yr]	Natural gas market [%]
Cedar Hills Landfill (King County) Bioenergy WA/Puget Sound Energy	Landfill	1,600,000	0.5%
Roosevelt Landfill (Republic Services) Klickitat County PUD	Landfill	2,102,400	0.7%
South Treatment Plant (King County) Puget Sound Energy	Wastewater treatment	300,000	0.1%
Total		4,002,400	1.3%

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 identified 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.

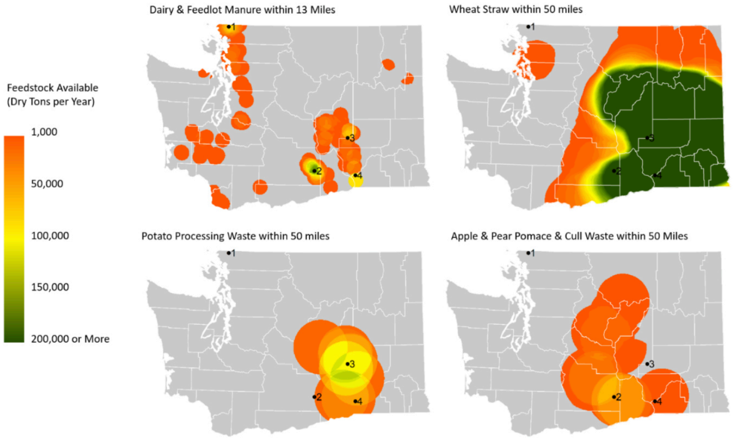

Figure C-1.2: Identification of potential sites for agricultural symbiosis projects for generation of renewable natural gas in Washington.

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].

Table C-1.4: Availability of cattle manure, wheat straw and pomace in selected sites in Washington State within the specified distance.

Nearby City	Label Number	Manure [50] (13 miles) [dry tons/yr]	Wheat straw [51] (50 miles) [dry tons/yr]	Apple & Pear Pomace [52] (50 miles) [dry tons/yr]
Lynden	1	89,709	-	-
Sunnyside	2	210,673	254,853	58,407
Warden	3	75,577	643,203	-
Burbank	4	115,754	596,176	2,158

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.

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.

Nearby City	Label Number	Manure (13 miles) [dry tons/yr]	Wheat straw (50 miles) [dry tons/yr]	Apple & Pear Pomace (50 miles) [dry tons/yr]
Sunnyside	2	146,018	87,611	58,407

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-1.6: 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.

Nearby City	Label Number	Biogas Potential [billion cuft/yr]	Methane Potential [billion cuft/yr]	RNG Potential [MMBtu/yr]
Sunnyside	2	3.84	1.56	~1,500,000

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.

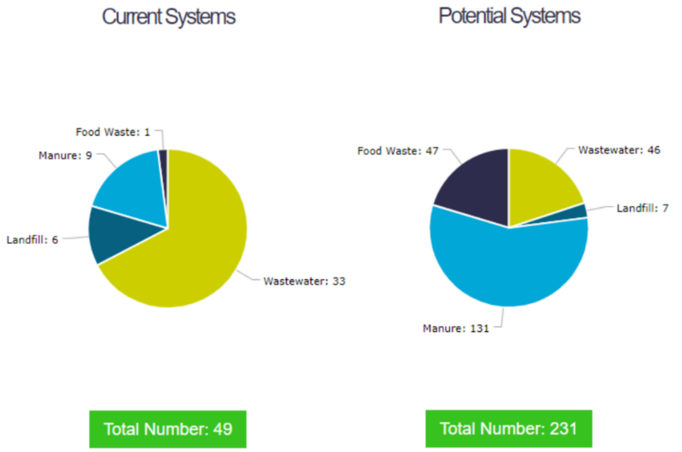

Figure C-1.3: Current and potential biogas projects in Washington State according to the American Biogas Council.

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.

Table C-1.7: Potential biogas production in Washington State based on estimates from the American Biogas Council.

Type	Production	Biogas Potential [billion cuft/yr]
Manure	7.2 million tons/yr	15
Food waste	2.37 million tons/yr	12.97
Landfill	-	-
Wastewater treatment plants	163 gallons/day	0.94
Total	**-**	**28.96**

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_2e/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 (NO_x) reduced by 75-95%
- Particle matter (PM) reduced by up to 90%
- Sulfur oxide (SO_x) 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

[1] "Farm Income and Wealth Statistics," 2021. Accessed: Jun. 23, 2023. [Online]. Available: https://www.ers.usda.gov/data-products/farm-income-and-wealth-statistics.aspx.

[2] "The Future of Farming: Strategic Plan for Washington Agriculture 2020 and Beyond," Accessed: Jun. 23, 2023. [Online]. Available: https://farmlandinfo.org/sample_documents/the-future-of-farming-strategic-plan-for-washington-agriculture-2020-and-beyond/.

[3] "Harnessing Renewable Natural Gas for Low-Carbon Fuel: A Roadmap for Washington State," 2017. Accessed: Jun. 23, 2023. [Online]. Available: https://www.commerce.wa.gov/wp-content/uploads/2018/02/Energy-RNG-Roadmap-for-Washington-Jan-2018.pdf.

[4] "Building a Resilient Future in Food and Farming," National Sustainable Agriculture Coalition, May 28, 2020. Accessed: Jun. 23, 2023. [Online]. Available: https://sustainableagriculture.net/blog/building-resilient-future-food-and-farming.

[5] "Washington Industrial Waste Coordination (Industrial Symbiosis) Program Recommendations," 2019. Accessed: Jun. 23, 2023. [Online]. Available: https://www.light-house.org/wp-content/uploads/2021/11/IWC-Program-Final-Report-12-18-19.pdf.

[6] R. L. Skaggs, A. M. Coleman, T. E. Seiple, and A. R. Milbrandt, "Waste-to-Energy biofuel production potential for selected feedstocks in the conterminous United States," Renewable and Sustainable Energy Reviews, vol. 82, pp. 2640–2651, Feb. 2018, doi: https://doi.org/10.1016/j.rser.2017.09.107.

[7] A. Badgett and A. Milbrandt, "A summary of standards and practices for wet waste streams used in waste-to-energy technologies in the United States," Renewable and Sustainable Energy Reviews, vol. 117, p. 109425, Jan. 2020, doi: https://doi.org/10.1016/j.rser.2019.109425.

[8] "Economic Drivers of Food Loss at the Farm and Pre-Retail Sectors: A Look at the Produce Supply Chain in the United States," Usda.gov, 2018. Accessed: Jun. 23, 2023. [Online]. Available: https://www.ers.usda.gov/publications/pub-details/?pubid=95778.

[9] J. C. Buzby, H. Farah-Wells, and J. Hyman, "The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States," SSRN Electronic Journal, vol. 121, 2014, doi: https://doi.org/10.2139/ssrn.2501659.

[10] "Advancing Organics Management in Washington State: The Waste to Fuels Technology Partnership 2019- 2021 Biennium," Washington State Department of Ecology, 2022. Accessed: Jun. 23, 2023. [Online]. Available: https://apps.ecology.wa.gov/publications/documents/2207002.pdf.

[11] T. Lim et al., "Increasing the Value of Animal Manure for Farmers," Economic Research Service Administrative Publication Number, vol. 109, 2023, Accessed: Jun. 23, 2023. [Online]. Available: https://www.ers.usda.gov/webdocs/publications/106089/ap-109.pdf?v=5168.4.

[12] "Biosolids: Organic Materials Management," Accessed: Jun. 23, 2023. [Online]. Available: https://calrecycle.ca.gov/organics/biosolids/.

[13] "Loop Biosolids. Turn your dirt around," Accessed: Jun. 23, 2023. [Online]. Available: https://kingcounty.gov/services/environment/wastewater/resource-recovery/loop-biosolids/biosolids.aspx#:~:text=The%20Washington%20State%20Department%20of,keep%20biosolids%20out%20of%20landfills.

[14] King County Biosolids Program Strategic Plan 2018–2037," Accessed: Jun. 23, 2023. [Online]. Available: https://kingcounty.gov/~/media/services/environment/wastewater/resource-recovery/plans/1711_KC-WTD-Biosolids-2018-2037-Strategic-Plan-rev2.ashx?la=en#:~:text=Finally%2C%20the%20Washington%20State%20Department,a%20beneficial%20use%20of%20biosolids.&text=As%20a%20result%20of%20this,considered%20further%20for%20WTD%20biosolids.

[15] A. Badgett, E. Newes, and A. Milbrandt, "Economic analysis of wet waste-to-energy resources in the United States," Energy, vol. 176, pp. 224–234, Jun. 2019, doi: https://doi.org/10.1016/j.energy.2019.03.188.

[16] K. Cantrell, K. Ro, D. Mahajan, M. Anjom, and P. G. Hunt, "Role of Thermochemical Conversion in Livestock Waste-to-Energy Treatments: Obstacles and Opportunities," Industrial & Engineering Chemistry Research, vol. 46, no. 26, pp. 8918–8927, Dec. 2007, doi: https://doi.org/10.1021/ie0616895.

[17] P. McKendry, "Energy production from biomass (part 2): conversion technologies," Bioresource Technology, vol. 83, no. 1, pp. 47–54, May 2002, doi: https://doi.org/10.1016/s0960-8524(01)00119-5.

[18] J. E. Amonette, M. Garcia-Perez, D. Sjoding, and Mark Raymond Fuchs, "Biochar from Biomass and its Potential Agronomic and Environmental Use in Washington: A Promising Alternative to Drawdown Carbon from the Atmosphere and Develop a New Industry," Mar. 2016, doi: https://doi.org/10.2172/1314415.

[19] R.W. Nachenius, F. Ronsse, R.H. Venderbosch, W. Prins, "Chapter Two – Biomass Pyrolysis," Advances in Chemical Engineering, vol. 42, pp. 75-139, Jan. 2013, doi: https://doi.org/10.1016/B978-0-12-386505-2.00002-X.

[20] A. J. Ward, P. J. Hobbs, P. J. Holliman, and D. L. Jones, "Optimisation of the anaerobic digestion of agricultural resources," Bioresource Technology, vol. 99, no. 17, pp. 7928–7940, Nov. 2008, doi: https://doi.org/10.1016/j.biortech.2008.02.044.

[21] X. Li et al., "Evaluation of Biogas Production Performance and Dynamics of the Microbial Community in Different Straws," vol. 27, no. 3, pp. 524–534, Mar. 2017, doi: https://doi.org/10.4014/jmb.1608.08062.

[22] L. Chen and H. Neibling, "Anaerobic Digestion Basics," uidaho.edu, Jun. 2014. Accessed: Jun. 23, 2023. [Online]. Available: https://www.uidaho.edu/-/media/UIdaho-Responsive/Files/Extension/publications/cis/cis1215.pdf?la=en.

[23] D. Elliott, P. Biller, A. Ross, A. Schmidt, and S. Jones, "Hydrothermal liquefaction of biomass: Developments from batch to continuous process," Bioresource Technology, vol. 178, pp. 147–156, Feb. 2015, doi: https://doi.org/10.1016/j.biortech.2014.09.132.

[24] L. Grande, I. Pedroarena, S. A. Korili, and A. Gil, "Hydrothermal Liquefaction of Biomass as One of the Most Promising Alternatives for the Synthesis of Advanced Liquid Biofuels: A Review," Materials, vol. 14, no. 18, p. 5286, Sep. 2021, doi: https://doi.org/10.3390/ma14185286.

[25] Jason. S. Midgett, B. E. Stevens, A. J. Dassey, J. J. Spivey, and Chandra. S. Theegala, "Assessing Feedstocks and Catalysts for Production of Bio-Oils from Hydrothermal Liquefaction," Waste and Biomass Valorization, vol. 3, no. 3, pp. 259–268, Jun. 2012, doi: https://doi.org/10.1007/s12649-012-9129-3.

[26] "Ecology, 2019. Compost. Washington Department of Ecology. Accessed: Jun. 23, 2023. [Online]. Available: https://ecology.wa.gov/Waste-Toxics/Reducing-recycling-waste/Waste-reduction-programs/Organic-materials/Managing-organics-compost.

[27] K. Dhamodharan, V. S. Varma, C. Veluchamy, A. Pugazhendhi, and K. Rajendran, "Emission of volatile organic compounds from composting: A review on assessment, treatment and perspectives," Science of The Total Environment, vol. 695, p. 133725, Dec. 2019, doi: https://doi.org/10.1016/j.scitotenv.2019.133725.

[28] "Anaerobic Digestion (Biogas) | CSANR | Washington State University," Center for Sustaining Agriculture and Natural Resources. Accessed: Jun. 23, 2023. [Online]. Available: https://csanr.wsu.edu/publications-library/energy/anaerobic-digestion/.

[29] F. Tambone, P. Genevini, G. D'Imporzano, and F. Adani, "Assessing amendment properties of digestate by studying the organic matter composition and the degree of biological stability during the anaerobic digestion of the organic fraction of MSW," Bioresource Technology, vol. 100, no. 12, pp. 3140–3142, Jun. 2009, doi: https://doi.org/10.1016/j.biortech.2009.02.012.

[30] K. Paritosh, S. K. Kushwaha, M. Yadav, N. Pareek, A. Chawade, and V. Vivekanand, "Food Waste to Energy: An Overview of Sustainable Approaches for Food Waste Management and Nutrient Recycling," BioMed Research International, vol. 2017, pp. 1–19, 2017, doi: https://doi.org/10.1155/2017/2370927.

[31] C. Kell, "Anaerobic Co-Digestion of Fruit Juice Industry Wastes with Lignocellulosic Biomass," Thesis, Stellenbosch University, 2019. Accessed: Jun. 23, 2023. [Online]. Available: https://scholar.sun.ac.za/server/api/core/bitstreams/e4b56802-9e4f-4707-9cda-68820325e1e0/content.

[32] M. Pöschl, S. Ward, and P. Owende, "Evaluation of energy efficiency of various biogas production and utilization pathways," Applied Energy, vol. 87, no. 11, pp. 3305–3321, Nov. 2010, doi: https://doi.org/10.1016/j.apenergy.2010.05.011.

[33] Thiago Edwiges, Laercio Mantovani Frare, J. Henrique, Jin Mi Triolo, X. Flotats, and Silva, "Methane potential of fruit and vegetable waste: an evaluation of the semi-continuous anaerobic mono-digestion," Environmental Technology, vol. 41, no. 7, pp. 921–930, Sep. 2018, doi: https://doi.org/10.1080/09593330.2018.1515262.

[34] J. Houghton, S. Weatherwax, and J. Ferrell, "Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda," Jun. 2006, doi: https://doi.org/10.2172/1218382.

[35] Federal Agricultural Research Centre. Results of the biogas program of measurements. Agency for Renewable Resources; Gülzow, Germany, 2005.

[36] J. Mata-Alvarez, S. Macé, and P. Llabrés, "Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives," Bioresource Technology, vol. 74, no. 1, pp. 3–16, Aug. 2000, doi: https://doi.org/10.1016/s0960-8524(00)00023-7.

[37] B. K. Ahring and J. Munck, "Method for treating biomass and organic waste with the purpose of generating desired biologically based products," Google Patents. Accessed: Jun. 23, 2023. [Online]. Available: https://patents.google.com/patent/WO2006032282A1/en.

[38] N. Dutta, R. Garrison, M. Usman, and B. K. Ahring, "Enhancing methane production of anaerobic digested sewage sludge by advanced wet oxidation & steam explosion pretreatment," Environmental Technology & Innovation, vol. 28, p. 102923, Nov. 2022, doi: https://doi.org/10.1016/j.eti.2022.102923.

[39] N. Dutta, A. T. Giduthuri, M. Usman Khan, R. Garrison, and B. K. Ahring, "Improved valorization of sewage sludge in the circular economy by anaerobic digestion: Impact of an innovative pretreatment technology," Waste Management, vol. 154, pp. 105–112, Dec. 2022, doi: https://doi.org/10.1016/j.wasman.2022.09.035.

[40] B. Ahring, "DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review. An Advanced Pretreatment/Anaerobic Digestion (APAD) Technology for Increased conversion of Sewage Sludge to Bio-natural gas in small-scale wastewater plants of less than five dry ton sewage sludge per day," 2021. Accessed: Jun. 23, 2023. [Online]. Available: https://www.energy.gov/sites/default/files/2021-04/beto-13-peer-review-2021-organic-ahring.pdf.

[41] M. U. Khan et al., "Current status of biogas upgrading for direct biomethane use: A review," Renewable and Sustainable Energy Reviews, vol. 149, p. 111343, Oct. 2021, doi: https://doi.org/10.1016/j.rser.2021.111343.

[42] "Biomethane for Transportation Opportunities for Washington State A report for the Western Washington Clean Cities Coalition," Washington State University, Nov. 2011. Accessed: Jun. 23, 2023. [Online]. Available: https://energy.wsu.edu/Documents/Biomethane_For_Transportation_WWCleanCities.pdf

[43] T. McCarthy, "Use of biogas: problems and solutions concerning trace components," GWF, vol. 139, no. 4, Apr. 1998, Accessed: Jun. 23, 2023. [Online]. Available: https://www.osti.gov/etdeweb/biblio/622057.

[44] "Washington Biogas and Energy Potential | American Biogas Council," americanbiogascouncil.org. Accessed: Jun. 23, 2023. [Online]. Available: https://americanbiogascouncil.org/resources/state-profiles/washington/.

[45] O. W. Awe, Y. Zhao, A. Nzihou, D. P. Minh, and N. Lyczko, "A Review of Biogas Utilisation, Purification and Upgrading Technologies," Waste and Biomass Valorization, vol. 8, no. 2, pp. 267–283, Jan. 2017, doi: https://doi.org/10.1007/s12649-016-9826-4.

[46] S. A. Hosseinipour and M. Mehrpooya, "Comparison of the biogas upgrading methods as a transportation fuel," Renewable Energy, vol. 130, pp. 641–655, Jan. 2019, doi: https://doi.org/10.1016/j.renene.2018.06.089.

[47] "Leveraging Natural Gas to Reduce Greenhouse Gas Emissions," Center for Climate and Energy Solutions, Jun. 12, 2013. https://www.c2es.org/document/leveraging-natural-gas-to-reduce-greenhouse-gas-emissions/.

[48] U.S. Energy Information Administration, 2015. Washington State Profile and Energy Estimates.

[49] “Promoting Renewable Natural Gas in Washington State,” Dec. 2018. Accessed: Jun. 23, 2023. [Online]. Available: https://www.commerce.wa.gov/wp-content/uploads/2019/01/Energy-Promoting-RNG-in-Washington-State.pdf.

[50] T. Seiple and A. Milbrandt, “National Wet Waste Inventory (NWWI),” data.mendeley.com, vol. 1, Jul. 2020, doi: https://doi.org/10.17632/f4dxm3mb94.1.

[51] Saad, “Physical Properties of Wheat Straw Varieties Cultivated Under Different Climatic and Soil Conditions in Three Continents,” American Journal of Engineering and Applied Sciences, vol. 5, no. 2, pp. 98–106, Feb. 2012, doi: https://doi.org/10.3844/ajeassp.2012.98.106.

[52] M. G. Lobo and E. Dorta, “Utilization and Management of Horticultural Waste,” Postharvest Technology of Perishable Horticultural Commodities, pp. 639–666, 2019, doi: https://doi.org/10.1016/b978-0-12-813276-0.00019-5.

[53] “Alternative Fuels Data Center: Renewable Fuel Standard,” Energy.gov, 2019. https://afdc.energy.gov/laws/RFS.html.

[54] “Low Carbon Fuel Standard | California Air Resources Board,” ww2.arb.ca.gov. https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard.

[55] “LCFS Pathway Certified Carbon Intensities | California Air Resources Board,” ww2.arb.ca.gov. Accessed: Jun. 23, 2023. [Online]. Available: https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities.

[56] R. Meyer, “Dispatching Direct Use Achieving Greenhouse Gas Reductions with Natural Gas in Homes and Businesses,” American Gas Association, 2015. Accessed: Jun. 23, 2023. [Online]. Available: https://www.homeinnovation.com/-/media/Files/Standards_Development/NGBS/2018_Development_Process/Prop_6150-2.pdf.

Appendix D

Agriculture Symbiosis International Profiles

1. Overview

As a component of our targeted research to inform this report, we conducted a global scan of agriculture symbiosis examples and produced these short descriptions.

This appendix is intended to: 1) demonstrate the great variety of agriculturally-relevant symbiosis opportunities that have been realized across a range of geographic, political, and economic conditions around the world; 2) underline the potential for modest small-scale partnerships to evolve into major multi-stakeholder operations with large, locally-important economic footprints; and 3) highlight the variety of conditions under which these associations began and some of the impetus for how they grew into what they are today.

Among the following examples, we are sharing both true multi-party industrial symbiosis examples, as well as some key examples of in-house circularity that we found especially compelling. As described in our report, optimizing the use and reuse of energy, water and organic materials within a business's facilities and across its operations is often an important first step to developing more complex symbiotic associations.

This is just a sampling of global agriculture symbiosis examples and is by no means exhaustive. The majority of case studies we investigated were from Europe, with a few excellent examples also coming from Asia.

1.1 Solrød Biogas - Denmark

This project emerged from an effort to utilize decaying seaweed that washed up on local beaches, and was creating a nuisance odor for residents and tourists. The solution identified by stakeholders was to generate biogas using the seaweed as a feedstock. The successful experiment prompted further consideration of other existing resources. Today Solrød Biogas, owned in part by the municipality of Solrød, utilizes over 190,000 tons of biomass feedstocks per year from local industries, from several distinct waste streams. The biomass is used primarily for the production of heat and electricity to replace fossil fuel inputs, but it also generates other key products. Local 'waste' resources are key to their success, as well as national policies, grants, subsidies, and academic and research engagement.

In addition to seaweed, major bio-feedstocks include lemon-derived pectin and carrageenan (a biotech waste), as well as general organic pulp, and manure from local farmers. The biogas is produced through a cascading system, which utilizes 55% more of the raw materials than would otherwise be used. The contained nature of the process also reduces the methane emissions that would otherwise occur. This results in a CO_2-neutral biogas which can replace fossil fuel energy when it is used for vehicles, sold to the grid, or used for combined heat and power (CHP). CHP uses an input like biogas to produce both electricity and useful heat, which in this case is used to heat the local district heating system owned by several municipalities. The biomass from the anaerobic digesters, as well as condensate from the gas cleaning process, are used to make a sustainably produced fertilizer for farmers to use. This reduces the need for chemical fertilizers, which results in less leaching of Phosphorous and Nitrogen into the aquatic environment. [1]

1.2 Kalundborg Symbiosis – Denmark

Kalundborg Symbiosis is a resource partnership between 16 entities, including both private companies and public operators. In a city of just 17,000 people, this project produces $28 million in yearly economic value, and saves 600,000 tons of CO_2 emissions. It began in the early 1970's as a collaboration when Statoil refinery, a petroleum producer, agreed to supply their excess gas to Gyproc, a gypsum producer, who used it to dry plasterboards in their ovens.

Because of the significant economic, cultural, and environmental benefits resulting from symbiosis the group has grown organically through a cooperative process over the 5 decades since their inception. Today the local municipality serves as a multi-utility providing distributed drinking water, process water, cooling water, wastewater treatment, water system management, and district heating. Ultimately, 20 different resources are exchanged between the participants, helping make Kalundborg one of the most mature and well-known examples of industrial symbiosis in the world. Excess gas is used for energy, biological sludge is delivered to farms, and fly ash from the power plant is supplied to cement manufactures. Half of one facility's energy came from within the network, and another was able to reduce its oil consumption costs by 95%. Within the next decade, they hope to use all resources and achieve zero waste. [2]-[5]

1.3 Biowert - Germany

This Swedish-German company began operating their first grass refinery in 2007. Their process converts locally grown meadow grass from permanent pastureland into a variety of products such as plastics, flavorings, and fertilizers, all of which are either recyclable or biodegradable. The generated plastics are more environmentally friendly than their petrol-based equivalents. The grass inputs are all locally produced and the company strives to use 100% recycled materials as part of their 'cradle to cradle' ethos.

Heat and water are cycled within the facility. Byproducts include a grass slurry, which can be fed into a biorefinery along with other inputs such as food waste. The gas produced is sent to a combined heat and power facility which covers the heat and energy needs of the entire facility, with excess being sent to the grid. Digestate from the biogas is turned into a fertilizer which can be applied to the fields of meadow grass which serve as their supply, and wastewater is reused for pretreatment of the grass. [6]-[9]

1.4 Sotenäs Symbiosis – Sweden

Before symbiosis, industry in Sotenäs was growing beyond what the region could handle. Seafood processors were prohibited from releasing any more process water into the local environment, and much of the waste was shipped to other regions in Sweden, as well as Norway and Denmark. To address this problem, local entrepreneurs and municipalities developed a new sustainable development strategy. As a result, a new biogas facility was built along with a wastewater purification plant. This allowed industrial activity to thrive while keeping emissions and waste from growing out of hand. The strategy was aided by an ongoing collaboration between Linköping University and the Symbiosis Centre, a municipal office which facilitates operations in Sotenäs.

Today many industrial sites and processing facilities exist in close proximity, allowing for easier exchanges of resources. These resources include organic waste and upcycled ocean waste (e.g. plastics, nets, and other debris) which are processed and fed into a biogas and wastewater facility. Other inputs are received from factories and fish facilities, which are exchanged for energy, water, and fertilizers as outputs. The biogas facility, for example, gives energy to a land-based fish farm, Smögenlax, which in turn provides sludge which can be used to make biogas. A Swedish Algae Farm operation then uses the effluent from the fish farm to cultivate its algae and produce specialized chemicals. A host of other connections all contribute to a community-driven attempt to create a circular economy. Research suggests that symbiosis will continue to boost the GDP of the area, increase jobs, and strengthen regional identity. [10]-[12]

1.5 Swedish Algae Factory

Located in Gothenburg, Sweden, the Swedish Algae Factory cultivates diatom algae to extract their silica shells. The algae is grown in a large greenhouse, and the materials extracted in a nearby facility. The resulting product, Algica, can be used as an environmentally friendly component of personal care products or as an efficiency-enhancing component of solar panels.

The algae is continuously collected by a self-propelled harvester. Nutrient-rich water that would otherwise have to be cleaned is taken from nearby food industry. The water is cycled through the algae system which removes nitrogen and phosphorous, and is then clean enough to send back to the food industry. This reduces wastewater and avoids effects such as eutrophication from runoff. Any waste biomass from production is used to create biofuel, converted to fertilizer, or used as livestock feed.

They have also partnered with a land-based fish farm, Smögenlax. Located in Sotenäs, Sweden, wastewater from the fish is cycled through the algae growing area to remove nitrogen and phosphorous, which allows it to be cycled back into the ponds. Some of the algae biomass is also used as feed for the fish. This operation shares connections with the greater symbiosis network in Sotenäs. [11], [13]-[15]

1.6 British Sugar, Wissington Factory – United Kingdom

British Sugar's Wissington factory was established in 1925. Today it is the largest beet sugar operation in the UK, and one of the largest in Europe, partnering with several hundred farmers who supply them with sugar beets. An initial focus on trying to use every available byproduct from sugar beet processing has led to the formation of many joint ventures. At least twelve coproducts have been identified, including betaine (used in cosmetics), bioethanol, CO_2, and electricity. Development of these additional products has led to increased sugar revenue, and greatly increased co-product revenue.

Methane from an anaerobic digester is used as fuel at a CHP plant, which in turn sends CO_2 to a horticulture complex. In addition, the CHP plant provides energy for the first bioethanol plant in the UK, established in 2007, which British Sugar established at Wissington. They also plan to introduce a spirulina plant to produce algae as feed for livestock. The plant would utilize excess boiler gas in the process. The company is continuously analyzing new ways to utilize any flows that may currently go to waste. [16]-[19]

1.7 Nanjangud Industrial Area – India

Nanjangud is an industrial area in India with 45 facilities, surrounded by a large agricultural community. The main focus is production of sugar and coffee. Around 900,000 tons of waste residues are produced annually by the partnering industries, and 99.5% of these residuals are being reused or recycled at least once within or across companies.

91% of the residuals are biomass. Most of that is bagasse, a fibrous sugar cane byproduct with high energy and low nutritional content. The bagasse is combusted within the industrial area to meet its 4 MW of power needs. The remaining 36 MW is sent to the grid. Boiler and fly ash are generated as a byproduct, which can serve as soil amendments for local farmers. The rest of the biomass residuals are food wastes that either directly or with processing, can generate fertilizers for local agriculture. In one example of resource exchange, an oil extraction facility provides boiler fuel to a food processing facility, which in turn sends spent coffee as feedstock back to the oil extractor.

90% of the reused products go to facilities within 20km of the industrial area, with two thirds of that going to direct reuse. Waste that was already similar to existing commodities tends to be sold to recyclers, while less standard waste like food residues are used within the industrial area. This arrangement came about organically, with no advance planning, perhaps due to a high degree of trust and shared norms among the partners. Ultimately the synergies that have been identified correlate with increased product sales and market success. The industry partners are actively seeking ways they can put to use the ash that currently makes up the last 0.5% of residuals that are not yet recycled. [20], [21]

1.8 GreenLab Skive – Denmark

A green, circular energy park that generates onsite renewable energy for participating companies. A variety of renewables, including solar and offshore-wind are currently producing power, and there are plans to also make use of green hydrogen. The park employs a system called SymbiosisNet which monitors data and energy usage, while supporting efficient exchange. There is a strong research aspect to the park which encourages testing of new methods and technologies in partnership with Danish universities.

GreenLab utilizes innovative electric power distribution methods, such as sector coupling which stores electricity in an intermediary industry. They are one of the first Power-to-X facilities, meaning they convert clean energy into a transportable form for use in transportation and industry. A planned large-scale green hydrogen production plant developed by Green Hydrogen Systems will facilitate these efforts.

Organic waste from local farms is used in the production of jet fuel and food proteins, while manure serves as a feedstock for their biogas facility. The residual fibers from biogas production feed into a neighboring facility which produces biochar and pyrolysis-gas. The CO_2 byproduct from the biogas facility will be used with the green hydrogen to produce bio-methanol, while any extra green hydrogen may result in boosts to biogas production. One plant uses invasive starfish to produce organic proteins for animal feed, while another will upcycle soiled plastic to create new products.[22]-[25]

1.9 Dutch Greenhouse Agriculture

Dutch greenhouses are renowned for their quality and efficiency. Though the Netherlands is small geographically, its vast array of greenhouses covering 80% of their cultivated land have helped it to become the second largest exporter of agricultural products in the world (Washington Post, Nov 21, 2022). This is in part due to their use of a “precision farming” system that allows detailed analysis and precise application of water and other inputs. These, among other innovations such as improvements to greenhouse heat retention, allow greater production and more efficient use of resources. This is aided by ongoing research, like that being done by the Dutch food research hub Wageningen University and Research. The greenhouse industry does face some challenges, such as the high energy demanded by plant lights which contribute to light pollution, and the potential pollution of surrounding surface waters. However, there are some examples of how these issues might be addressed. The Duijvestijn Tomatoes company for example, uses geothermal energy and a hydroponics system. The roots are kept in rockwool, which allows even greater water efficiency. The closed-circuit aspect of their water system means that the plants receive only as much water as they need, so that there is no runoff. This means there’s no avenue for any fertilizers to escape and pollute the surroundings. They also pump waste CO_2 from a local Shell oil refinery to help feed their plants and reduce emissions.[26]-[29]

1.10 Guitang Group – China

The Guitang Group began as a cane sugar business in the Guangxi Zhuang Autonomous Region, an area of China that accounts for 40% of the country’s sugar production. The group also uses sugar cane residue, known as bagasse, as an input at a large paper production facility. Efforts to use bagasse and other wastes have led to several new production lines including alcohol, pulp, toilet paper, calcium carbonate, cement, and power generation. The company has continually seen new opportunities for symbiosis over their four decades in operation, resulting in new earnings while generating less pollution and emissions.

In addition to bagasse, other fiber sources are used such as locally produced rice and bamboo waste. Ash and other organic wastes from sugar production can be used in cement production, alcohol byproducts are used to create fertilizer, and the calcium carbonate plant utilizes wastewater from paper mills, among other resource exchanges. Organic wastes are also sent back as soil amendments and organic fertilizer to the fields that supply sugar canes. These are provided by the Guitang Group at no cost to the local farmers whose products are processed by the Group. This is done to encourage use of organic practices which can ultimately raise the valuation of the Guitang Groups products. More facilities and connections are planned for future development.

A challenge the group faces is that demand for their waste-derived products tends to exceed the available local feedstock supply . As a result the group has worked to acquire feedstocks from competitors. That effort has succeeded in part due to government mandates requiring smaller producers to send their byproducts to the Guitang Group. [30]-[32]

1.11 Volta Greentech – Sweden

Volta Greentech is a land-based algae producer located in Sweden. The algae produced is used as feed for local cattle, which substantially reduces greenhouses gases produced by the cattle. This is possible because the algae contains a compound known as bromoform, which in cows inhibits the digestive enzyme that forms methane. Based on the available data, roughly 60 grams of seaweed feed per cow each day, is enough to reduce methane emissions by roughly 80%. The technology is licensed from the Australia agency CSIRO.

At Volta Greentech, electricity is fully provided by renewable sources, and waste heat from nearby industries is utilized. The seawater used for cultivating the seaweed is pumped in and recirculated, saving on water usage. Plans are in motion to create a symbiotic relationship with the plant-based food company Mycorena, using the CO_2 waste produced through fungi fermentation to help bolster algae growth.[33]-[37]

1.12 100% Fish Project – Iceland

Run by the Iceland Ocean Cluster, the goal of this project is to maximize efficient use of fish in ways that minimize waste, support new business opportunities and employment, and increase the value of every fish. Compared to the rest of Europe and North America where roughly 50% of the average cod's weight is wasted, industry in Iceland has reached roughly 80% utilization of white fish.

Success in this regard has been primarily due to research and development in the areas of processing and handling. New parts have been utilized such as bones and dried heads, and companies that specialize in using fishery by-products have grown and developed innovative processes. New products have ranged from cosmetics to proteins to pharmaceuticals.

In Iceland the government offers general supports for green business and innovation, which has helped circular practices to flourish. There are also private sector initiatives, such as CleanTech Iceland and Hafið, which both focus on sustainable tech solutions including in the fishing industry. The Svartsengi Resource Park also engages industrial symbiosis and is entirely driven by private entities like HS Orka, with activities ranging from geothermal power to fish drying to R&D.[38-40]

References

[1] “Solrød Biogas - Towards a Circular Economy,” 2015. Available: https://task37.ieabioenergy.com/wp-content/uploads/sites/32/2022/03/Solrod_Biogas_Case_Story_web.pdf

[2] CEF “Kalundborg — The World’s First Fully Functional Industrial Symbiosis,” CEF, Aug. 29, 2016. https://corporateecoforum.com/kalundborg-worlds-first-fully-functional-industrial-symbiosis/

[3] “Kalundborg industrial symbiosis,” wwf.panda.org. https://wwf.panda.org/wwf_news/?204431/Kalundborg-industrial-symbiosis

[4] “Kalundborg Symbiosis: six decades of a circular approach to production | European Circular Economy Stakeholder Platform,” circulareconomy.europa.eu. https://circulareconomy.europa.eu/platform/en/good-practices/kalundborg-symbiosis-six-decades-circular-approach-production

[5] “Kalundborg Symbiosis - The world’s leading industrial symbiosis,” Kalundborg Symbiosis. https://www.symbiosis.dk/en/

[6] “BIOWERT GRASS BIOREFINERY BIOBASED PLASTICS, GERMANY IEA Bioenergy Task 37 BIOGAS IN SOCIETY A Case Story.” Available: https://www.ieabioenergy.com/wp-content/uploads/2019/07/IEA_grass-refinery_end.pdf

[7] Biowert Industries, “BIOWERT - bio based industry,” biowert.com. https://biowert.com/company/cradletocradle

[8] N. Hatvani, M. Van Den Oever, K. Mateffy, and A. Koos, “Bio-based Business Models: specific and general learnings from recent good practice cases in different business sectors,” 2022, doi: https://doi.org/10.36253/bae-10820.

[9] Pollution Solutions, “Green Solutions from Green Company,” Pollution Solutions Online. https://www.pollutionsolutions-online.com/news/consultancy-services/19/biowert-industrie-gmbh/green-solutions-from-green-company/20959

[10] “How Sweden’s most sustainable industrial cluster was created,” liu.se. https://liu.se/en/news-item/sa-skapades-sveriges-mest-hallbara-industrikluster

[11] Smogenlax “SCH Illustrations,” Smogenlax.se. https://smogenlax.se/wp-content/uploads/2021/03/SCH_illustrations_eng.pdf (accessed Jun. 07, 2023).

[12] S. Harris, “Socio-economic assessment of the Sotenäs Industrial Symbiosis Network,” RISE, Jan. 2018. https://www.ri.se/sites/default/files/2023-04/Bilaga%203%20Socio-economic%20assessment%20Soten%C3%A4s%20Industrial%20symbiosis.pdf (accessed Jun. 07, 2023).

[13] M. Martin and S. Harris, “Prospecting the sustainability implications of an emerging industrial symbiosis network,” Resources, Conservation and Recycling, vol. 138, pp. 246–256, Nov. 2018, doi: https://doi.org/10.1016/j.resconrec.2018.07.026.

https://smogenlax.se/wp-content/uploads/2021/03/SCH_illustrations_eng.pdf[14]“Swedish Algae Factory,” swedishalgaefactory.com. https://www.swedishalgaefactory.com/

[15] “The Swedish Algae Factory - Nordregio,” archive.nordregio.se. https://archive.nordregio.se/en/Publications/Publications-2016/GREEN-GROWTH-IN-NORDIC-REGIONS-50-ways-to-make-/Blue-growth-/The-Swedish-Algae-Factory-/index.html

[16] “Britain opens first bioethanol plant,” Reuters, Nov. 22, 2007. Available: https://www.reuters.com/article/environment-biofuels-britain-dc-idUSL224214720071122

[17] J. Bates “British Sugar plans could lead to world-first protein product plant,” Lynn News, Aug. 23, 2022. https://www.lynnnews.co.uk/news/british-sugar-plans-could-lead-to-world-first-protein-produc-9270355/

[18] “Make the most of these beets: increasing diversity and building resilience in the sugar industry,” European Circular Economy Stakeholder Platform, Apr. 11, 2018. https://circulareconomy.europa.eu/platform/en/good-practices/make-most-these-beets-increasing-diversity-and-building-resilience-sugar-industry

[19] S. W. Short, C. Y. Barlow, and M. Chertow, “From Refining Sugar to Growing Tomatoes Industrial Ecology and Business Model Evolution,” Jan. 2014.

[20] A. Bain, M. Shenoy, W. Ashton, and M. Chertow, “Industrial symbiosis and waste recovery in an Indian industrial area,” Resources, Conservation and Recycling, vol. 54, no. 12, pp. 1278–1287, Oct. 2010, doi: https://doi.org/10.1016/j.resconrec.2010.04.007.

[21] W. S. Ashton and A. C. Bain, “Assessing the ‘Short Mental Distance’ in Eco-Industrial Networks,” Journal of Industrial Ecology, vol. 16, no. 1, pp. 70–82, Feb. 2012, doi: https://doi.org/10.1111/j.1530-9290.2011.00453.x.

[22] “About,” GreenLab. https://www.greenlab.dk/about/

[23] “Danish town seeks green transition redemption – DW – 07/18/2022,” dw.com. https://www.dw.com/en/danish-town-embraces-circular-economy-in-bid-to-go-green/a-62478930

[24] “Greenhyscale | Greenhyscale,” Greenhyscale.eu, 2023. https://greenhyscale.eu/

[25] “GreenLab,” State of Green. https://stateofgreen.com/en/solution-providers/greenlab/

[26] A. Peters, “These eerily beautiful glowing buildings are the Netherlands’ massive network of greenhouses,” Fastcompany.com, Mar. 13, 2020. https://www.fastcompany.com/90476025/these-eerily-beautiful-glowing-buildings-are-the-netherlands-massive-network-of-greenhouses (accessed Jun. 07, 2023).

[27] D. Welle (www.dw.com), “Could high-tech Netherlands-style farming feed the world? | DW | 23.01.2019,” DW.COM, Jan. 23, 2019. https://www.dw.com/en/could-high-tech-netherlands-style-farming-feed-the-world/a-47105412

[28] J. Strickler, “High-Tech Greenhouses Could Be The Future Of Agriculture,” Forbes. https://www.forbes.com/sites/jordanstrickler/2020/08/28/high-tech-greenhouses-could-be-the-future-of-agriculture/?sh=211d3b96380f

[29] K. Whiting, “The Netherlands is a leader in sustainable agriculture,” World Economic Forum, Nov. 27, 2019. https://www.weforum.org/agenda/2019/11/netherlands-dutch-farming-agriculture-sustainable/

[30] D. Lew, “Eco Chains in China The Guitang Group - Industrial Ecology,” Dr. Darrin Lew, Sep. 28, 2021. https://www.drdarrinlew.us/industrial-ecology/ecochains-in-china-the-guitang-group.html

[31] M. Benedetti, “10 – The experience of the Guitang Group in the Guanxi province in China, leading the industrial development of the region through intra and inter firm symbiosis implementation – MAESTRI – Energy and resource management systems for improved efficiency in the process industries,” May 09, 2017. https://maestri-spire.eu/experience-guitang-group-guanxi-province-china-leading-industrial-development-region-intra-inter-firm-symbiosis-implementation/

[32] Q. ZHU, E. A. LOWE, Y. WEI, and D. BARNES, “Industrial Symbiosis in China: A Case Study of the Guitang Group,” Journal of Industrial Ecology, vol. 11, no. 1, pp. 31–42, Oct. 2008, doi: https://doi.org/10.1162/jiec.2007.929.

[33] J. Cornall, “Swedish startup Volta Greentech looks to build world’s largest algae factory,” dairyreporter.com, May 31, 2021. https://www.dairyreporter.com/Article/2021/05/31/Swedish-startup-Volta-Greentech-looks-to-build-world-s-largest-algae-factory

[34] L. Manning, “Swedish seaweed startup Volta Greentech raises $2m to grow low-emissions livestock feed,” AFN, Jun. 09, 2021. https://agfundernews.com/volta-greentech-raises-2m-to-grow-livestock-seaweed-supplement

[35] Mycorena, “Mycorena and Volta Greentech Receive Vinnova Grant to Co-develop Carbon-Neutral Fermentation Scale-up Process,” Mycorena. https://mycorena.com/mycotalks/mycorena-and-volta-greentech-receive-vinnova-grant-to-co-develop-carbon-neutral-fermentation-scale-up-process

[36] “Sea Forest gets funding to commercialize CSIRO seaweed feed tech,” AFN, Feb. 15, 2021. https://agfundernews.com/sea-forest-cattle-seaweed-supplement-pregnancy-test-get-government-funding-in-australia

[37] Voltagreentech.com, 2023. https://www.voltagreentech.com/production/

[38] “100% Fish | Íslenski sjávarklasinn,” www.sjavarklasinn.is. https://www.sjavarklasinn.is/en/100-fish/

[39] A. Berlina, N. Mikkola, & J. Teräs “Industrial Symbiosis A key driver of Green Growth in Nordic Regions?” Accessed: Jun. 17, 2023. [Online]. Available: https://www.diva-portal.org/smash/get/diva2:917631/FULLTEXT01.pdf

[40] I. H. Johnsen, A. N. Berlina, G. Lindberg, J. Teräs, L. Olsen, and N. Mikkola, “The potential of industrial symbiosis as a key driver of green growth in Nordic regions,” Jan. 2015.