Pyrolysis Matrix pg 1

Product Classification: Pyrolysis	Wood Vinegar (Pyro-ligneous Acid)	Carbon Black	Biochar	Activated Carbon
Minimum feedstock required	24,800 BDT/year	Unknown	5,000,000 BDT/year	Unknown
Carbon storage	No	Yes (products)	Yes (char)	Yes (char)
Technology readiness level	5	4-5	9	9
Commercial readiness level	2-3	3	5	9
Feedstock use	Non-merchantable	Non-merchantable	Non-merchantable	Non-merchantable
International markets	Yes	Yes	Yes	Yes
Potential market size	Small	Large	Medium	M-L
Research or analysis need	High	High	High	Medium
Can JIWPI influence outcomes?	Low	Medium	Medium	Medium

Pyrolysis Matrix pg 2

Product Classification: Pyrolysis	**Torrefied Wood (Biocoal)**	**Renewable Natural Gas**
Minimum feedstock required	90,000 BDT/y	250,000 BDT/yr (GTI Stockton)
Carbon storage	No	Possible (CCS)
Technology readiness level	7-8	6
Commercial readiness level	6	5
Feedstock use	Non-merchantable	Non-merchantable
International markets	Yes	Yes
Potential market size	Medium	Large
Research or analysis need	Low	High
Can JIWPI influence outcomes?	Medium	High

Pyrolysis Matrix pg 3

Product Classification: Pyrolysis	**Fischer - Tropsch Fuels**	**Gas Fermentation for Fuels**	**Transportation Fuels via Fast Pyrolysis and Hydroprocessing**	**Lignocellulosic Ethanol (non pyrolysis based)**
Minimum feedstock required	68,000 BDT/yr (Red Rock Biofuels)	100,000 tons of biomass/yr feedstock (Aemetis, Inc.)	300,000 BDT/yr feedstock (SPI Camino site)	100,000 BDT/Year (Axens/Anderson Biomass)
Carbon storage	Possible (CCS)	No	Yes (Biochar)	No
Technology readiness level	7	8	6	8
Commercial readiness level	6-7	6	5	6
Feedstock use	Non-merchantable	Non-merchantable	Non-merchantable	Non-merchantable
International markets	Yes	Yes	Yes	Yes
Potential market size	Large	Large	Large	Large
Research or analysis need	Medium	Medium	Medium	High
Can JIWPI influence outcomes?	High	Medium	Medium	Low

Chapter I. **Innovation in pyrolysis**

1. Preface

Pyrolysis is a thermochemical conversion process that decomposes woody biomass into liquid, gaseous, and solid products under inert or low oxygen conditions. The temperature and residence time of the pyrolysis process affect the proportion of each type of product produced. Higher operation temperatures decompose more biomass into gaseous products. Conversely, lower operation temperatures produce a greater proportion of solid products, like biochar (Bridgewater et al., 1999). Fast pyrolysis is a sub-category of pyrolysis that utilizes higher temperatures. Fast pyrolysis rapidly decomposes biomass at approximately 500 degrees Celsius in order to maximize liquid yield (Pollard et al., 2012). Slow pyrolysis is also performed in the absence of oxygen but at lower temperatures of about 300 degrees Celsius. The process is considered "slow" because the residence time for vapors ranges from 5-30 minutes compared to an order of a few seconds during fast pyrolysis (Gerewal et al, 2018).

Pyrolysis products include: pyroligneous acid, carbon black, biochar, activated carbon, torrefied, wood, renewable natural gas, Fisher-Trope diesel, gas fermentation and gasification, bio-oil, and bioethanol.

Given its range of products, pyrolysis is a promising technological platform for wood product innovation. As discussed previously, if markets for pyrolysis products are developed, they may incentivize the removal of woody biomass from California forests.

The matrix is an overview of the current and potential landscape for each product in California. To support this preliminary assessment, the chapter summarizes existing literature to evaluate the technological and commercial readiness of each pyrolysis product. We also discuss the potential influence that the JIWPI may have in product development.

Table 1. Existing Pyrolysis Operations in California

Facility Name	**Location**	**Products Produced**	**Scale**	**Currently Utilizes Wood Feedstock?**
Kore Infrastructure	El Segunda, CA	Bio-gas, Bio-hydrogen, Biochar	Not yet operational	No (but is ideal if made cheaper)
Corigin Solutions LLC	Merced, CA	Biochar, Wood Vinegar	10 tons/hour	No (but is ideal if made cheaper)
Alta Roundwood	Anderson, CA	Biochar		Yes
Loyalton	Loyalton, CA	Biochar		Yes

Note: Proposed facilities are described in detail in specific product sections. Facilities using woody biomass primarily for power generation are not included.

References

Bridgwater, A. V., Meier, D., & Radlein, D. (1999). An overview of fast pyrolysis of biomass. *Organic geochemistry*, *30*(12), 1479-1493.

Grewal, A., Abbey, Lord, Gunupuru, L.R., 2018. Production, prospects and potential application of pyroligneous acid in agriculture. J. Anal. Appl. Pyrolysis 135, 152–159. https://doi.org/10.1016/j.jaap.2018.09.008

Pollard, A. S., Rover, M. R., & Brown, R. C. (2012). Characterization of bio-oil recovered as stage fractions with unique chemical and physical properties. *Journal of Analytical and Applied Pyrolysis*, *93*, 129-138.

Product: Pyro-ligneous acid

Product Description

One of the common by-products of slow pyrolysis is pyroligneous acid (PLA). PLA is an oxygenated, crude organic liquid at room temperature, and is produced following the capture and condensation of pyrolysis gases (Grewal et al., 2018). During slow pyrolysis, cellulose and lignins from wood or agricultural feedstock are carbonized at roughly 300 degrees Celsius (Grewal et al., 2018). Once the gases are captured, the condensed liquid undergoes a three-month purification process to produce three layers of liquid: light oil, crude brown PLA, and wood tar (Grewal et al., 2018).

PLA is often referred to as wood vinegar, liquid smoke, bio-oil, or wood distillate (Grewal et al., 2018). Wood vinegar has potential applications as a natural alternative herbicide, pesticide, and insecticide as well as plant growth (Grewal et al., 2018; Luo et al., 2019; Mohan et al., 2006; Simma et al., 2017). In California, one patented wood vinegar product is certified by the state as an organic input suitable for organic farming (Corigin Solutions, LLC, 2019). Novel applications include food additives and flavoring (Grewal et al., 2018), an animal feed supplement to reduce bacterial growth (Kupittayanant and Kupittayanant, 2017), and an application to facilitate compost decomposition (Nurhayati et al., 2006).

Several variables impact wood vinegar production quality and consistency. Temperature in particular can impact PLA use and effectiveness. For example, a study of bamboo and spruce PLA application found that vegetable seed germination and subsequent growth were promoted at temperatures of up to 250 degrees Celsius (Fagernas et al,. 2015). However, there was a strong inhibition on germination and radicle growth using vinegar produced at 250 to 400 degrees Celsius (Fagernas et al,. 2015). Feedstock moisture content and hardness also impact quality (Truesdall, 2019). In addition, the residence time of vapors during the slow pyrolysis process (ranging between 5-30 minutes) contribute to product consistency (Grewal et al., 2018).

Existing Capacity

Currently, there are no commercial scale facilities producing wood vinegar in California. One Merced-based company, Corigin Solutions LLC, produces a wood vinegar product called "Coriphol" but not yet at a commercial scale (Truesdall, 2019). The facility is capable of processing 10 tons of feedstock per hour.

Justification

The multiple uses of wood vinegar highlight its potential to spur growth in numerous high-value markets. Should California, which is already dominant in organic agriculture, invest in PLA, it may develop a competitive advantage for natural pesticides, herbicides, and insecticides, as well as a growth enhancer.

Market Indicators

It is estimated that the global market for wood vinegar will reach $6.7 million USD by 2022 (CAGR, 2016). According to a 2019 survey in Australia and New Zealand, one liter of wood vinegar ranges from $2-$12, with an average price of $4.63 per liter (Robb and Joseph, 2019). Production is concentrated in Asia, but exists at a small scale in Australia, New Zealand, Chile, France, Finland, and many other countries. Many of the technical and feasibility studies to date were based in Asian countries (Grewal et al., 2018). In the US, wood vinegar is more commonly used for smoke flavoring or as a food additive (Grewal et al., 2018). The "liquid smoke" global market was valued at $56.5 million dollars in 2018 (Grand View Research, 2019).

The wood vinegar market has potential to expand as farmers seek to reduce usage of fossil chemical inputs to agriculture, lucrative pharmaceutical uses are developed, and its efficacy for plant growth ability is solidified (Bauer, 2017).

Barriers to product or process innovation and growth

Multiple barriers exist that hinder the wood vinegar market. In California, the largest barrier to producing wood vinegar from forest biomass is feedstock inaccessibility; the cost to access slash and other non-merchantable wood is too high (Truesdall, 2019). Consequently, small-scale wood vinegar production across the country appears to utilize agricultural biomass. In California, almond shells and other fruit orchard debris are the most common feedstock (Truesdall, 2019).

Market growth may also be limited because wood vinegar is not the highest value pyrolysis product. As described in a 2015 study, PLA production may only be economical if integrated into sawmills or combined with production of other pyrolysis products such as wood pellets (Fagernäs et al., 2015).

There are also a myriad of regulations that complicate production. USDA regulations are different and more restrictive than European regulations (Bauer, 2017). Efficacy concerns also abound, and there remains the fact that a potential market favors "smaller-scale farmers that favor green practices" (Robb and Joseph, 2019).

Research Gaps

There is a considerable need for research into the use and efficacy of conifer feedstock for wood vinegar production, especially using species native to California forests. Most research to date has concentrated on bamboo PLA production due to its popularity in Asia. In Nordic countries, spruce feedstock has also been examined. However, there is a lack of research regarding the use of softwoods found in California. This is a critical research gap because different tree species have different chemical and structural compositions that influence the specifics of a pyrolysis operation, and the JIWPI is primarily focused on non-merchantable conifer feedstock for pyrolysis applications.

There also is a need to research less well-known (but potentially high value) uses of wood vinegar. Currently, it is not clear how effective PLA is when applied to animal feed or homeopathic medicine (Mohan et al., 2006; Theapparat et al., 2018). Thus, efficacy studies would be useful to understand the liquid's impact on high-value California crops like almonds and avocados. Research is also needed to understand if California tree species are suitable in terms of flavoring and preservation for liquid smoke production.

Product Substitution

The use of wood vinegar in limited markets in the developing world may displace limited amounts of fossil-fuel derived chemical pesticides, herbicides, and insecticides. Commercial markets, however, are slowly developing in China and Australia, especially with organic farmers who prefer or require natural approaches to pest control and/or utilize wood vinegar for its seed germination enhancement properties (Robb and Joseph, 2019). This presents a large opportunity: although wood vinegar does not store or sequester carbon, it theoretically could displace a sizeable number of fossil-fuel derived products.

Additionally, wood vinegar application for plant growth has the potential to displace fertilizers, pesticides, and insecticides. Wood vinegar could potentially reduce the need for certain types of antibiotics as an animal feed additive.

Opportunities for JIWPI Influence

- Conduct conifer feedstock studies to determine suitability for PLA production.
- Conduct PLA efficacy trials using conifer feedstock for fertilizer, pesticide, insecticide, and liquid smoke applications.
- Develop a demonstration-scale facility that produces PLA in combination with other pyrolysis products
- Streamline or advance favorable statewide waste diversion regulations to reduce forest biomass feedstock costs for PLA production.

MATRIX EXPLANATION

- **Minimum feedstock required:** *24,800 BDT/year*. Facilities focused on PLA production can process 10 tons of feedstock per hour with the potential for more to operate at full capacity. Amount extrapolated from this estimate; based on assumption that facility operates 85% of the year.
- **Carbon storage** *No.* Wood vinegar does not store or sequester carbon, since it is a volatile liquid and dissipates into the atmosphere when applied in agricultural or other settings.
- **Technology readiness level** *5.* Engineering and pilot scale production is ongoing, and PLA produced from agricultural biomass is sold in small-scale operations. Technological

research in terms of product efficacy using wood feedstock is still needed to support commercial-scale production. Temperature consistency in slow pyrolysis operations remains a challenge and impacts product efficacy.

- **Commercial readiness level** *2-3.* There are not yet commercial-scale production in California, although some small operations like Corigin Solutions, LLC are producing wood vinegar in combination with other pyrolysis products. Market research is sparse and derived from secondary sources like CAGR, and competitive analysis and value-chain studies are not yet completed. Permitting, especially in regards to air quality, is challenging for pyrolysis operations but does not appear specific to PLA production.
- **Feedstock use** *Non-merchantable wood.* Limited technical studies (Fagernas et al,. 2015, Theapparat et al., 2018) cite the use of small-diameter woody biomass as suitable for production, but the majority utilize agricultural biomass.
- **International markets** *Yes.* Wood vinegar application in small-scale agriculture is common across Asia and is growing in popularity among some organic farmers in Australia, New Zealand, Chile, and many other countries (CAGR, 2016).
- **Potential market size** *Small.* It is estimated that the global market for wood vinegar will reach $6.7 million USD by 2022 (CAGR, 2016). Markets will likely attract organic farmers initially, although this growing niche is significantly smaller than conventional agriculture. Interestingly, market size has the potential to increase if the cost to access wood biomass is reduced in California and no longer impedes production.
- **Research or analysis need** *High*. Although limited technical studies exist, significant research is still needed to determine PLA's efficacy on plants and crops grown in California. Similarly, technical studies of PLA production using forest species common to California are also necessary to determine feasibility. Permitting for use in conventional or organic agriculture needs examination; Corigin LLC, has obtained a "Certificate for Registration of Organic Materials" in California for its PLA product but federal regulations remain unclear.
- **Can JIWPI influence outcomes?** *Low*. JIWPI may support research into using conifer feedstock for PLA production, but the most significant market barrier remaining is product efficacy and marketing. The JIWPI however, may facilitate some market growth for PLA is by lowering the cost of accessing forest woody biomass; until then, orchard residues and other agriculture waste will dominate as the more economical feedstock.

References

Bauer, L., 2017. Biomass Pyrolysis Comes of Age : Biofuels Digest [WWW Document]. BioFuels Dig. URL https://www.biofuelsdigest.com/bdigest/2017/06/08/biomass-pyrolysis-comes-of-age/ (accessed 11.9.19).

BioGreen Energy, E.T. for I. (ETIA), 2019. Wood Vinegar (Pure Smoke Water) Bio-Stimulant [WWW Document]. URL https://greenmanchar.com.au/products/wood-vinegar-puresmokewater (accessed 10.18.19).

CAGR, R. and M., 2016. Wood Vinegar Market by Pyrolysis Method (Slow Pyrolysis, Fast Pyrolysis, and Intermediate Pyrolysis), Application (Agriculture, Animal Feed, Food, Medicinal, and Consumer Products), and Region - Global Forecast to 2022 [WWW Document]. Res. Mark. URL https://www.researchandmarkets.com/reports/3989538/wood-vinegar-market-by-pyrolysis-method-slow (accessed 10.18.19).

Corigin Solutions, LLC, 2019. Products: Coriphol [WWW Document]. Corigin Solut. LLC. URL https://www.corigin.co/products/coriphol.html (accessed 11.10.19).

Fagernäs, L., Kuoppala, E., Arpiainen, V., 2015. Composition, Utilization and Economic Assessment of Torrefaction Condensates. Energy Fuels 29, 3134–3142. https://doi.org/10.1021/acs.energyfuels.5b00004

Grand View Research., 2019. Liquid Smoke Market Size, Share Trends | Industry Report, 2019-2025. Retrieved November 30, 2019, from https://www.grandviewresearch.com/industry-analysis/liquid-smoke-market

Grewal, A., Abbey, Lord, Gunupuru, L.R., 2018. Production, prospects and potential application of pyroligneous acid in agriculture. J. Anal. Appl. Pyrolysis 135, 152–159. https://doi.org/10.1016/j.jaap.2018.09.008

Luo, X., Wang, Z., Meki, K., Wang, X., Liu, B., Zheng, H., You, X., Li, F., 2019. Effect of co-application of wood vinegar and biochar on seed germination and seedling growth. J. Soils Sediments 1–11. https://doi.org/10.1007/s11368-019-02365-9

Mohan, D., Pittman, C.U., Steele, P.H., 2006. Pyrolysis of Wood/Biomass for Bio-oil: A Critical Review. Energy Fuels 20, 848–889. https://doi.org/10.1021/ef0502397

Robb, S., Joseph, S., 2019. A Report on the Value of Biochar and Wood Vinegar: Practical Experience of Users in Australia and New Zealand. Australia-New Zealand Biochar Initiative.

Theapparat, Y., Chandumpai, A., Faroongsarng, D., 2018. Physicochemistry and Utilization of Wood Vinegar from Carbonization of Tropical Biomass Waste | IntechOpen, in: Tropical Forests: New Edition. InTech Open, p. Chapter 8.

Truesdall, K., 2019. Interview with Corigin.

Product: Carbon Black

Product Description

Carbon black is a form of manufactured carbon that is conventionally produced through the incomplete combustion of fossil fuels. A majority of carbon black produced is utilized as a filler and strengthening component in rubber tires, while it is also used as a filler and strengthening component in other various rubber and plastic products. Carbon black can be derived from woody biomass, as well as other forms of biomass such as agricultural waste. Research has shown that carbon black can be derived from biomass pyrolysis oil as well as from bio-derived chars (Fan and Fowler, 2018; Toth et al., 2018).

Existing capacity

There are no known commercial facilities in California or globally that are producing carbon black from woody biomass.

Justification

Although carbon black derived from woody biomass is in the research and development stage, the potential to partially displace conventionally produced carbon black is large. Scaled production of bio-derived carbon black would add an additional demand for small-diameter woody biomass within California, thereby assisting in creating a market for currently unmerchantable wood. Additionally, carbon black derived from biomass results in less carbon emissions than conventionally produced carbon black. Studies indicate that biomass derived carbon black is composed of between 60 and 85 percent carbon (McCaffrey, 2019).

Market indicators

The production of carbon black from woody biomass is still in the research and development stage. Recent research suggests that carbon black produced from woody biomass pyrolysis oil is equivalent to medium grade carbon black produced from fossil fuels (Toth et al., 2018) and, therefore, can be utilized as an additive in numerous products that use conventionally produced carbon black. Further scaling of production is necessary to identify if woody biomass derived carbon black can compete in the conventional market. The price of conventionally produced carbon black is tied to the price of oil.

Barriers to product or process innovation and growth

Barriers to growing the woody-biomass carbon black market are related to both its technological and commercial immaturity. Only small-scale, research studies have successfully produced carbon black derived from woody biomass. Scaled production needs to be proven before the product can become commercially viable. Additionally, although there is a large existing market for conventional carbon black, there is no guarantee that consumers will switch to biomass derived carbon black, even if it is competitively priced due to uncertainty regarding product quality. However, studies indicating that biomass derived carbon black can be produced at commercial grade are promising (Toth et al., 2018).

Research gaps

As previously discussed, the production of carbon black from woody biomass (as well as other biomass feedstocks) is limited to small-scale research (Fan and Fowler, 2018; Toth et al., 2018). Large-scale studies as well as operational experience with large-scale processing facilities are necessary to confirm that production can be successful and competitive at a commercial scale. Additionally, the lowering of the oxygen content of biomass pyrolysis oil is essential to scale woody biomass-derived carbon black production (Toth et al., 2018).

Product substitution

In 2018, the world market size for carbon black was approximately $17.2 billion USD. Additionally, the market is expected to increase in size by six percent over the next six years. In terms of products, a majority of this demand is coming from tire manufacturing. Regionally, Asia Pacific has the greatest demand for carbon black (Grand View Research, 2019).

With a large and increasing demand for conventionally-produced carbon black, carbon black derived from woody biomass has the potential to tap into a thriving global market. Existing companies that utilize carbon black and other conventional carbon products are trying to switch to bio-derived carbon alternatives. Goodyear Tires recently announced that they would replace all of their fossil-fuel derived processing oils with oil derived from soybeans by 2040 (Manly, 2019).

Opportunities for JIWPI Influence

- Partner with research institution(s) to develop a trial, commercial scale carbon black production facility to prove scalability.
- Partner with transportation research centers (The UC Berkeley / Davis Institute for Transportation Studies) and CalTrans to prove markets.
- Introduce carbon black derived from woody biomass pyrolysis oil as a low-carbon alternative to carbon black conventionally produced from fossil fuels, including through legislation, procurement, or testing
- Other market development activities including policy, finance and/or technology incubation.

MATRIX EXPLANATION

- **Minimum feedstock required** *Unknown.* Carbon black produced from woody biomass has only been completed at the small-scale, research level.
- **Carbon storage** *Yes.* Carbon black produced from agricultural biomass has been shown to be composed of between 60 and 80 percent carbon (McCaffrey, 2019). Additionally, carbon black stays in products for a relatively long amount of time. For example, rubber tires (the product for which the majority of carbon black is used) take between approximately 80 and 100 years to decompose in a landfill (Alsaleh & Sattler, 2014).
- **Technology readiness level** *4-5.* Carbon black produced from woody biomass has yet to be scaled to commercial level.
- **Commercial readiness level** *3*. Although the conventional market for carbon black in rubber tires and other rubber products is robust, carbon black derived from woody biomass is not yet commercially produced and there is more research needed to determine whether it would be seen as a viable substitute in the market.
- **Feedstock use:** *Non-merchantable wood.*
- **International markets** *Yes.* Carbon black is used in a variety of rubber and plastic products worldwide. In 2018, the global market size for carbon black was approximately $17.2 billion USD (Grand View Research, 2019).
- **Potential market size** *L.* If carbon black derived from woody biomass was scaled to commercial production, there is a large conventional market in which it could play a role. Therefore, it could substantially increase demand for small-diameter woody biomass within California.

- **Research or analysis need** *High*. Research needed to prove scaled production can produce carbon black at the same quality as smaller research studies (Toth et al., 2018).
- **Can JIWPI influence outcomes?** *Medium*. A lack of technical maturity hinders JIWPI's ability to promote or develop markets.

References

Alsaleh, A., & Sattler, M. L. (2014). Waste Tire Pyrolysis: Influential Parameters and Product Properties. Current Sustainable/Renewable Energy Reports, 1(4), 129–135. https://doi.org/10.1007/s40518-014-0019-0

Fan, Y., & Fowler, G. D. (2018). The Potential of Pyrolytic Biomass as a Sustainable Biofiller for Styrene-Butadiene Rubber. In M. A. Chowdhury (Ed.), Advanced Surface Engineering Research. https://doi.org/10.5772/intechopen.79994

Grand View Research. (2019). Carbon Black Market Size, Share & Trends Analysis Report By Application (Tires, High-performance Coatings, Plastics), By Region (North America, Middle East & Africa, Asia Pacific, Europe), And Segment Forecasts, 2019—2025 (p. 113) [Industry Report].

McCaffrey, Z. (2019, October 28). *Carbon black research questions interview with Zach McCaffrey at USDA - bioproducts*.

Toth, P., Vikström, T., Molinder, R., & Wiinikka, H. (2018). Structure of carbon black continuously produced from biomass pyrolysis oil. Green Chemistry, 20(17), 3981–3992. https://doi.org/10.1039/C8GC01539B

Product: Biochar

Product Description
Biochar is a recalcitrant charcoal created from pyrolysis of biomass at high temperatures (300 to 700 degrees Celsius) (Anderson et al., 2013). Biochar can be used in many capacities, including as an animal feed, as a soil amendment, and in water filtration. When biochar is added to agricultural soils, it can increase crop yield by enhancing soil hydrological and nutrient properties (Pourhashem et al., 2019).

Existing capacity
There are several companies producing and selling biochar from forest biomass in California. North America is currently the largest consumer of biochar and is where more than 80 percent of medium and large scale manufacturers are located (Grand View Research, 2019). Key industry players include BSEI (Oregon and China), Airex Energy Inc. (Canada), and Diacarbon Energy (Canada), which all use forest biomass as a feedstock (Grand View Research, 2019).

Justification
The economic and environmental benefits provided by biochar justify further research into methods to help scale this nascent market. Biochar has the capacity to improve crop yields in

agricultural soil, reduce nutrient runoff and fertilizer application, increase water retention, and sequester carbon (Pourhashem et al., 2019). Biochar has also been demonstrated(?) to reduce the release of nitrogenous gases from fertilizers as well as carbon dioxide emissions from tilling (Pourhashem et al., 2019).

Market indicators

Although still in its nascent stages, a market for biochar in the US is steadily growing. The USBI estimated that 200,000 bone dry tons of biomass are consumed yearly to create biochar and that 35,000-70,000 tons per year of biochar are currently produced in the US (USBI, 2018). Another market report estimated a global market size of $1.3 billion in 2018, with demand estimated at 395.3 kilo-tons a year (Grand View Research, 2019).

Barriers to product or process innovation and growth

The large amount of capital required to construct a new pyrolysis facility is one of the main barriers to growth in the biochar industry. According to Pourhashem et al. (2019), the total investment costs for a large-scale biochar facility (2,000 tons/day) can be more than $400 million. Additionally, uncertainty surrounding future biochar prices make it difficult for market establishment (Campbell et al., 2018).

Research gaps

Standardization and certification of biochar products is a large research gap impeding market growth. Stronger definitions of biochar grades are needed to help improve industry standards (USBI, 2018). Additionally, there is limited research into policies that would facilitate payments for ecosystems services to farmers who manage their lands with biochar (Pourhashem et al., 2019).

Product substitution

Biochar has been shown to be an effective substitute for peat, which is most commonly used as a growing media in horticulture (Steiner & Harttung, 2014). Approximately 11 MMT of peat are used for horticultural purposes each year (Steiner & Harttung, 2014). Peat bogs are important ecosystems and are valuable carbon stores. However, when harvested and used for horticulture, peat decomposes quickly and becomes a source of greenhouse gases (Steiner & Harttung, 2014). Replacing peat with biochar, a stable form of carbon, would reduce the amount of carbon emissions in the horticulture industry.

However, biochar can be created from a range of feedstocks, most of which are existing waste streams. According to Kore Infrastructure, although wood pellets would be an ideal feedstock, agricultural and sewage waste is abundant for use and much less cost prohibitive.

Opportunities for JIWPI Influence

- Contributing to efforts to integrate biochar into California's climate policy in order to help subsidize the high cost of biochar production. For example, integration of biochar into the carbon offsets market would help provide financial subsidies for the product and drive market growth. In a number of interviews in the viticulture industry, many growers were aware of the benefits of using biochar, but that the product was too expensive.

Subsidizing biochar through climate policies could help engage this uncaptured share of the market.

MATRIX EXPLANATION

- **Minimum feedstock required: 2,000 tons/day.** According to Pourhashem et al. (2019), a large-scale biochar facility operates at a scale of around 2,000 tons/day. Amount extrapolated from this estimate; based on assumption that facility operates 85% of the year. Kore Infrastructure stated they process approximately one ton of mixed feedstock per hour at their pyrolysis facility**.** Approximately 20-25 percent of their feedstock becomes biochar. Other manufacturers have estimated their dry weight feedstock throughputs to be approximately 700 kilograms per hour (Lee et al., 2013).
- **Carbon storage** *Yes.* Biochar can have a carbon content of around 60-70 percent and has the capacity to remain sequestered in soils for thousands of years (Granastein et al., 2009; Laird et al., 2009).
- **Technology readiness level** *9.* Biochar is currently produced at a scale of 2,000 tons/day in large scale plants with at least two dozen globally recognized operating companies (Pourhashem et al., 2019; Polaris Market Research, 2019).
- **Commercial readiness level** *5.* Currently, markets for biochar are not well established as there is substantial volatility and uncertainty surrounding biochar prices (Campbell et al., 2018). Additionally, while farmers are considered the primary customers of biochar, wide adoption of biochar into agricultural practices has not yet been achieved (Polaris Market Research, 2019). Industry participants are now focusing on educating farmers to help scale the industry.
- **Feedstock use** *Non-merchantable wood.* Various types of feedstocks can be used to create biochar, including non-merchantable wood.
- **International markets** *Yes.* According to Grand View Research (2019), most biochar is manufactured in North America (80 percent) and in Europe. Large amounts of biochar are produced in collaboration with research groups and institutions in rural areas in China, Japan, Brazil, and Mexico
- **Potential market size** *Medium.* Polaris Market Research (2019) estimates the global biochar market will reach $3.23 billion by 2026, growing at a compound annual growth rate of 9.1%.
- **Research or analysis need** *High.* Standardization and certification of biochar products is a large research gap impeding market growth (USBI, 2018).
- **Can JIWPI influence outcomes?** *Medium*. Contributing to efforts to integrate biochar into California's climate policy can help subsidize the high cost of biochar and further spur the market.
- **Investment Potential.** According to Kore Infrastructure, biochar is not economically viable when produced by itself. Rather, it provides an additional revenue stream for pyrolysis facilities that are coproducing higher value products such as biogas and bio-oil. Investing in education for farmers about the benefits of biochar may help increase the scalability of biochar and help fund production of other pyrolysis products.

References

Campbell, R. M., Anderson, N. M., Daugaard, D. E., & Naughton, H. T. (2018). Financial viability of biofuel and biochar production from forest biomass in the face of market price volatility and uncertainty. Applied energy, 230, 330-343.

Grand View Research (2019). Biochar Market Size, Share & Trends Analysis Report By Technology (Gasification, Pyrolysis), By Application (Agriculture (Farming, Livestock)), By Region, And Segment Forecasts, 2019 - 2025. Retrieved from https://www.grandviewresearch.com/industry-analysis/biochar-market.

Polaris Market Research. (2019).Biochar Market Share, Size, Trends, & Industry Analysis Report, [By Technology (Gasification, Pyrolysis, Others), By Application (Agriculture {Livestock Farming, General Farming (Organic Farming, Inorganic Farming, Others)} Others), By Regions Segment Forecast, 2019 - 2026. Retrieved from https://www.kennethresearch.com/report-details/biochar-market/10082391.

Pourhashem, G., Hung, S. Y., Medlock, K. B., & Masiello, C. A. (2019). Policy support for biochar: Review and recommendations. GCB Bioenergy, 11(2), 364–380. https://doi.org/10.1111/gcbb.12582

Steiner, C., & Harttung, T. (2014). Biochar as a growing media additive and peat substitute. Solid Earth, 5(2), 995-999.

US Biochar Initiative (USBI). (2018). Survey and Analysis of the U.S. Biochar Industry. Retrieved from http://biochar-us.org/sites/default/files/news-files/Preliminary%20Biochar%20Industry%20Report%2008162018_0.pdf.

PRODUCT: Activated Carbon

Product Description

Activated carbon is a form of carbon that has been processed to make it extremely porous (Adeleke, 2018). This high porosity gives activated carbon a large surface area which increases its adsorption capacity. Activated carbon is used for a range of purposes, most commonly in potable water purification and sewage treatment (Grand View Research, 2019). In 2018, 40% of the total volume manufactured in the world was used for water treatment applications (Grand View Research, 2019).

Existing capacity

Although 10.8% of activated carbon business establishments are located in California (Adeleke, 2018), no commercial scale activated carbon facilities located in state were identified. However, Calgon Corporation has a reactivation manufacturing site located in Blue Lake, CA which recycles spent activated carbon.

Three companies dominate global market share: Kuraray Company Limited (50%), Cabot Corporation (20%), and Ingevity Corporation (8%) (Adeleke, 2018). Other key companies include Carbon Activated Corporation, Jacobi Carbons AB, Calgon Carbon Corp., Osaka Gas Chemical Co. Ltd., and Evoqua Water Technologies LLC (Grand View Research, 2019).

Justification

Activated carbon is an existing mature industry that utilizes woody material as a feedstock. Thus, there is a high potential for the integration of non-merchantable wood feedstock.

Market indicators

Activated carbon is a mature global market (Adeleke, 2018). In 2019, the global market amounted to 2.4 MMT and is projected to grow to approximately 5 MMT by 2021, growing at a CAGR of 8.2 percent (Beroe, 2018). The global industry is also projected to reach $353.5 million by 2023, growing at an annualized rate of 1.0 percent (Adeleke, 2018).

The production capacity in the US amounted to 0.256 MMT in 2018 (Beroe, 2018). Intensifying emission standards are anticipated to create a boon for the industry, as filtration for air and water pollution increases in demand (Adeleke, 2018). However, currently, in the US, exports account for 91% of industry revenue (Adeleke, 2018).

Currently, China is the biggest exporter of activated carbon, accounting for 18 percent of the current market, followed by the US (16 percent), Belgium (7 percent), and the Netherlands (6 percent) (Beroe, 2018). The Asia-Pacific region is also expected to have the fastest market growth, with a CAGR of 11.1 percent through 2022 (Shukla, 2016). All other regions are expected to experience market decline in response to the growth of the Asia-Pacific (Grand View Research, 2019).

Barriers to product or process innovation and growth

Activated carbon growth is largely confined by its high capital requirements. IBISWorld classified the activated carbon manufacturing industry as "moderately capital intensive" (Adeleke, 2018). They estimate that for every $1.00 spent on labor, manufacturers spend $0.15 on capital machinery and equipment. The price of feedstock is also a potentially large barrier to growth, as raw materials account for 68-72 percent of the final price (Market Reports World, 2019). Additionally, substitute products such as silica gel and super sand are expected to slow market growth (Market Reports World, 2019).

Environmental laws are another barrier to growth and may provide reason for the absence of activated carbon producers in California. For example, manufacturers are subject to the Clean Air Act as well as the Resource Conservation and Recovery Act and the Comprehensive Environmental Response, Compensation and Liability Act for handling and disposal of hazardous substances created during the production process (Adeleke, 2018). Additionally, as activated carbon is used in drinking water treatment facilities, manufacturers must adhere to the American Water Works Association standards. California environmental laws are commonly regarded as relatively strict compared to other states, which may be disincentivizing production in California.

Research gaps

Most research and development in the industry surrounds emerging end-uses in downstream markets, with emphasis currently placed on applications that can remove pathogens and contaminants (Adeleke, 2018). More research is needed to assess how California can encourage activated carbon production in state.

Product substitution

Activated carbon is most commonly used for water purification and water treatment, making up 49% of end user industries (Beroe, 2018). It is projected that by 2020 activated carbon feedstock will consist mainly of wood/coal (57%) and coconut shells (37%) (Beroe, 2018). The availability of coconut shells as a feedstock is highly vulnerable to adverse environmental conditions that affect coconut production. Common product substitutes for activated carbon filtration includes sand filtration and silica gel filters. Additional substitutes, such as granular rubber and coke breeze have been tested as substitutes for activated carbon but have not been used at a commercial scale (Beroe, 2018).

Opportunities for JIWPI Influence

- Investigate avenues for woody biomass to replace feedstocks currently being used in California facilities (if any exist)
- Research environmental laws and policies that may be disincentivizing activated carbon production in California

MATRIX EXPLANATION

- **Minimum feedstock required** *Unknown.*
- **Carbon storage** *Yes.*
- **Technology readiness level** *8-9.* Technological readiness is high as the level of research and development invested in technology change is low (Adeleke, 2018). Most research and development investment is driven by end uses in downstream markets.
- **Commercial readiness level** *9.* Activated carbon is a highly mature and globalized industry currently sold for a range of different end uses (Adeleke, 2018). Global market size is expected to reach $5.12 billion by 2022 (Shukla, 2016).
- **Feedstock use** *Non-merchantable.*
- **International markets** *Yes.* The activated carbon manufacturing industry is highly globalized (Adeleke, 2018). Key exporting countries include China (18 percent), US (16 percent), Belgium (7 percent), and the Netherlands (6 percent). The market across the Asia-Pacific region is expected to grow the fastest, at a compound annual growth rate (CAGR) of 11.1 percent through 2022 (Beroe, 2018; Shukla, 2016).
- **Potential market size** *Large***.** Global market size is projected to reach 2.5-5 MMT by 2021 growing at a CAGR of 8.2 percent and $5.12 billion by 2022 at a CAGR of 9.3 percent (Beroe, 2018; Shukla, 2016).
- **Research or analysis need** *Medium.* Market research on how to integrate non-merchantable wood from California forests into a mature global market is necessary.
- **Can JIWPI influence outcomes?** *Medium.* Investigate environmental laws in California that may be disincentivizing activated carbon production in state

References

Adeleke, V. (2018). IBIS World Industry Report OD4484 Activated Carbon Manufacturing in the US. IBISWorld.

Beroe (2018). Category Intelligence on Activated Carbon. Retrieved from https://www.beroeinc.com/category-intelligence/activated-carbon-market/.

Grand View Research. (2019). Activated Carbon Market Size, Share & Trends Analysis Report By Product (Powdered, Granular), By Application (Liquid, Gas), By End Use (Water Treatment, Air Purification), By Region, And Segment Forecasts, 2019 - 2025. Retrieved from https://www.grandviewresearch.com/industry-analysis/activated-carbon-market.

Market Reports World (2019). Activated Carbon Market - Growth, Trends, and Forecast (2019 - 2024). Retrieved from https://www.marketreportsworld.com/activated-carbon-market-growth-trends-and-forecast-2019-2024--13347362.

Shukla, S. (2016). Activated Carbon Market by Product Type (Powdered, Granular, and Others), End-Use (Water Treatment, Food & Beverage Processing, Pharmaceutical & Medical, Automotive, Air purification, and Other End-Uses), and Application (Liquid, and Gaseous) and - Global Opportunity Analysis and Industry Forecast, 2014-2022. Allied Market Research. Retrieved from https://www.globenewswire.com/news-release/2019/07/15/1882739/0/en/Global-Activated-Carbon-Market-Size-to-Reach-5-12-Billion-At-9-3-CAGR.html.

Product: Biocoal/Torrefied Wood

Definitions

Torrefied wood, also known as biocoal, is a product of partial pyrolysis. In this process, raw woody biomass is burned in an oxygenless environment at 250 to 300 degrees Celsius. Torrefaction removes much of the moisture and volatile compounds from biomass resulting in a product that has a higher energy density per unit mass compared to the raw feedstock. This higher density has the benefit of reducing the per Joule transportation cost of biomass. Additionally, one of the notable innovations within torrefaction technology is that the displaced volatile compounds are recaptured and burned as syngas, thus creating a more thermally efficient heating process that requires less energy input for production. The resulting biomass can be condensed and pelletized, creating a fuel with a similar energy density and handling properties as coal (Thrän et al., 2017). Because of this similarity, a common use for biocoal is to co-fire it within existing coal power plants since biocoal is considered carbon net-neutral (the carbon released from its burning is recaptured via tree growth) and completely lacks the heavy metal and sulfur emissions that come from coal.

Existing capacity

In 2015 approximately 26 Mt of torrefied wood was produced globally; 5 Mt of which came from US exports (Thrän et al., 2017). Production demand came primarily from Europe: European Union countries subsidize biomass for use as carbon-neutral bioenergy towards meeting their Paris Agreement goals. East Asian countries like China, Japan, and South Korea also make up a large portion of global demand.

In California, while some of the state's energy comes from woody biomass as a result of policies like SB 1122, the added cost of torrefaction to the high cost of forest woody biomass means that these facilities rely solely on raw materials rather than biocoal. That said, it is possible that a distributed network of satellite torrefaction facilities could, despite upfront costs, lead to overall cost savings at scale in California due to decreased transportation costs.

Justification

Torrefied wood has numerous benefits over raw biomass as bioenergy source. Torrefaction creates a product that is roughly 50% more energy dense, absent of most volatiles, and is mostly hydrophobic – meaning it can be stored with minimal risk of decay and carbon monoxide off-gassing (Thrän et al., 2017). The decreased moisture content and increased density also help reduce the often prohibitively high cost of transportation associated with forest residuals. Additionally, compared to the fossil fuels that it can displace, torrefied wood has relatively lower GHG emissions associated with its use. As mentioned above

Market indicators

Interest and research into torrefaction has seen a steady rise in the past decade as indicated by the number of scholarly papers on the topic (Ribeiro et al. 2018). This research has focused on technological advancements as well as market research into supply chains and consumer demand (Fritsche et al., 2019). Coupled with the large and quickly growing international markets for biocoal, this indicates a potentially bright future for the product. In particular, there are a number of large commercial scale facilities (producing > 50,000 tons/year) operating internationally (Ribeiro et al. 2018, Cremers et al. 2015). However, it is important to recognize that demand for torrefied wood is in part subsidized by government demand for green energy – often in the form of feed-in tariffs and feed-in premiums, though the exact schemes vary between EU countries (Banja et al., 2019).

Barriers to product or process innovation and growth

One of the primary concerns expressed by biocoal consumers is product consistency. Energy facilities would benefit from quality assurances regarding gridability, moisture content and energy balance as a means of increasing consumer trust (Wild et al., 2016).

Research gaps

Much of the ongoing research on torrefied wood relates to product consistency for end-users. Different feedstock sources (e.g. pine versus spruce) can lead to small but important differences in certain characteristics such as minimum ignition energy or biological degradation (Fritsche et al., 2019). Additionally, various preheating and densification techniques can also lead to differences in product quality and consistency (Fengler et al., 2017).

Product substitution

As mentioned above, torrefied wood has a similar energy density and handling properties as coal, allowing it to be co-fired within existing coal facilities. Promising research also demonstrates potential for full-scale coal substitution within steam powered trains using a process that requires minimal retrofitting of steam engines (Fengler et al., 2017). There is also potential for use of biocoal within high temperature industrial heat processes such as paper, cement, glass, ceramics and steel and iron production (Fritsche et al., 2019). Once again, limitations do remain in terms of inconsistency of biocoal pellets and the inability to fully match the energy density of coal.

Opportunities for JIWPI Influence

- The JIWPI should steer market research towards the potential for California derived torrefied wood to meet the growing demand from East Asian countries like Japan and South Korea. This could come in the form of seeking out Asian business partners and researching the potential demand quantity and price points for the type and quality of pellets that could be produced in California.
- Invest in research regarding the cost and benefits of constructing satellite torrefaction facilities in California as a means reducing the cost of transportation to biomass energy facilities.

MATRIX EXPLANATION

- **Minimum feedstock required**: *149,000 BDT/year.* In the United States, the Restoration Fuels facility in John Day, Oregon (construction to be completed in Q1 2020), is expected to produce 100,000 tons of product from 149,000 BDT/year. In Europe where markets for torrefied wood are boosted via government subsidies for green energy, the smallest commercial facilities require approximately 90,000 BDT/year (Cremers et al. 2015).
- **Carbon storage:** *No*. Considered carbon-neutral.
- **Technology readiness level:**l *7-8*. The John Day facility will be capable of producing >250 tons/day. A few European facilities also have similar production levels.
- **Commercial readiness level:** *6*. While numerous commercial facilities exist worldwide (primarily in Europe) the market is largely fueled by European government subsidy. Even despite the subsidies, many European facilities have been decommissioned or mothballed due to high production costs and unstable markets.
- **Feedstock use:** *Non-merchantable*. Can use various non-merchantable woody biomass feedstocks, from forest residues to sawdust.
- **International markets:** *Yes*. Large, growing demand particularly from European and East Asian countries expected. Market has grown globally from 6 Mt in 2006 to 26 Mt in 2015, with continued growth expected (Thrän et al., 2017).
- **Potential market size:** *Large*. Domestically there may be potential for conversion of local biomass electric facilities toward use of torrefied pellets. However, the greatest potential market lies from Asian countries like Japan and Korean, which combined are expected to have a demand of over 20 Mt of wood pellets per year by the mid-2020s (Thrän et al., 2017). Much of this demand is expected to be met by China and South East Asia countries, however there may still be a great deal of potential for California biomass within these markets.
- **Research or analysis need:** *Medium*. Need for more research into means of maintaining high levels of product quality across a range of feedstock sources including very small diameter forest residues.
- **Can JIWPI influence outcomes?** *Yes*. Two recommendations based on potential means of facilitating in-state use and international export of biocoal.

References

Banja, M., Sikkema, R., Jégard, M., Motola, V., & Dallemand, J.-F. (2019). Biomass for energy in the EU – The support framework. Energy Policy, 131, 215–228. https://doi.org/10.1016/j.enpol.2019.04.038

Cremers, Marcel, Jaap Koppenjan, Jan middlekamp, Joop Witkamp, Shahab Sokhensanj, Staffan Melin, Sebnem Madrali. (2014) Status overview of torrefaction technologies: a review of the commercialsation status of biomass torrefaction. IEA Bioenergy

Fengler, W. A., & Ward, D. A. (2017). Preserving Solid Fuel Firing in a Post-Coal World. 22.

Mody, J., Saveliev, R., Bar-ziv, E., & Perelman, M. (2014.). Production and characterization of biocoal for coal-fired boilers. Proceedings of the National Academy of Sciences. ASME Power Conference (2014).

Ribeiro, J., Godina, R., Matias, J., & Nunes, L. (2018). Future Perspectives of Biomass Torrefaction: Review of the Current State-Of-The-Art and Research Development. Sustainability, 10(7), 2323. https://doi.org/10.3390/su10072323

Thrän, D., Peetz, D., Schaubach, K., Mai-Moulin, T., Junginger, H. M., Lamers, P., & Visser, L. (2017). Global Wood Pellet Industry and Trade Study 2017. IEA Bioenergy Task 40.

Wild et al. 2016. Possible effects of torrefaction on biomass trade. IEA Bioenergy Task 40. April 2016.

Wilén, Carl, Kai Sipilä, Sanna Tuomi, Ilkka Hiltunen, Christian Lindfors, Esa Sipilä, Terttu-Leea Saarenpää & Markku Raiko. 2014. Wood torrefaction – market prospects and integration with the forest and energy industry. VTT Technology 163. 55 p.

Product: Renewable Natural Gas

Product Description
Deployment of fuels having a lower carbon intensity can help the state reach its goals for aggressive greenhouse gas emissions reduction.

One pathway to substantially reduce GHG and criteria pollutant emissions is by expanded use of renewable natural gas (RNG). RNG can be produced from a number of sources, such as digesters, wastewater treatment facilities, landfills and from thermal conversion of renewable carbonaceous materials like woody biomass.

Here, we target the thermal conversation of woody biomass to RNG via gasification and subsequent catalytic conversion. This is broadly known as methanation, or the Sabatier process.

Commercial suppliers of these technologies include Andritz and Haldor Topsoe A/S (GTI, 2019).

RNG is distinguished from biogas by its quality. RNG can be produced by upgrading biogas or syngas to be of an appropriate quality and make-up to supplement or replace natural gas. Most RNG being used in California and throughout the rest of the United States is produced from landfills (GTI, 2019).

Existing Capacity
We are not aware of any existing demonstrations of this technology using forest biomass. However, there have been at least two proposals for facilities producing RNG in California:

(1) The Gas Technology Institute has produced an engineering design for RNG production in Stockton, CA. The facility would operate at the DTE biomass power plant in Stockton, producing 3 BCF/yr RNG and displacing approx 170,000 tons of CO_2/yr (GTI, 2019).
(2) San Joaquin Renewables has announced intentions to develop an RNG production facility employing methanation on agricultural wood waste in McFarland, California (San Joaquin Renewables, 2019).

Justification
Renewable natural gas production and consumption has expanded dramatically in the United States in recent years, based on policy support by the U.S. Renewable Fuel Standard and California's low-carbon fuel standard. While much of this RNG is sourced from the anaerobic digestion of wet biomass (e.g. manure), it is possible to convert woody biomass to RNG using thermochemical processing.

Market Indicators
Several electricity and gas utilities in California, namely SoCalGas, have expressed an interest in the production and procurement of RNG as part of California's climate policy (SoCalGas, 2019).

Further, California has also passed a renewable gas standard (SB 1440), calling for an increasing share of RNG to be produced from biomass. The law was signed in 2018 by then-Governor Brown.

Barriers to product or process innovation and growth
The primary barrier to growth of RNG from forest biomass is the lack of a demonstration facility operating on woody biomass feedstock.

Research Gaps
See 'Barriers' above.

Product Substitution
RNG is a direct substitute for fossil-derived natural gas. Natural gas is a hydrocarbon gas mixture consisting primarily of methane. California is a large producer and consumer of natural gas, consuming over 2,000 BCF/yr.

Opportunities for JIWPI Influence

- Facilitate development of a demonstration facility.
- Other market development activities, including policy, finance, or technology incubation.

MATRIX EXPLANATION

- **Minimum feedstock required:** *250,000 BDT/yr*. The Gas Technology Institute has based their engineering design on a renewable natural gas (RNG) facility that would convert wood waste on a feedstock demand of 310,000 tons of biomass at 17% moisture. This is roughly 250,000 BDT (GTI, 2019).
- **Carbon storage:** *Possible*. The Gas Technology Institute included carbon capture and sequestration (CCS) as a possibility in their engineering design study.
- **Technology readiness level:** *6*. According to the Gas Technology Institute, there has been previous pilot-scale testing in the United States and commercial scale design work performed in Europe of RNG technologies using woody biomass as a feedstock. We are not aware of the demonstration of an actual system prototype in a relevant environment. (GTI, 2019)
- **Commercial readiness level:** *5*. A deep understanding of the target application and market (low-carbon fuels in California) has been achieved. However, we are not aware of any companies developing a facility in California that operates on forest biomass.
- **Feedstock use:** *Non-merchantable wood.* All lignocellulosic biomass, including forest and agricultural wastes, can be used.
- **International markets**: *Yes.* In Europe there is currently a large demand for locally produced RNG and biogas, however, we do not expect California to enter into the European market.
- **Potential market size:** *Large.* The National Renewable Energy Laboratory has estimated California's potential natural gas demand as a transportation fuel to be ~110 trillion Btu/year by 2030 (Penev, 2016). This is a market size of 110 BCF/yr, or roughly 9.5 million BDT/yr of wood demand.
- **Research or analysis need:** *High*. We are not aware of the demonstration of an actual system prototype in a relevant environment. As such, JIWPI could help facilitate the demonstration of this technology in CA.
- **Can JIWPI influence outcomes?** *High*. JIWPI could facilitate the development of a demonstration facility, or perform other market development activities, including policy, finance, or technology incubation.

References

Gas Technology Institute (GTI). (2019). *Low-Carbon Renewable Natural Gas (RNG) from Wood Wastes*. Retrieved from https://www.gti.energy/wp-content/uploads/2019/02/Low-Carbon-Renewable-Natural-Gas-RNG-from-Wood-Wastes-Final-Report-Feb2019.pdf

Penev, M., Melaina, M., Bush, B., Muratori, M., Warner, E., & Chen, Y. (2016). *Low-carbon natural gas for transportation: well-to-wheels emissions and potential market assessment in California* (No. NREL/TP-6A50-66538). National Renewable Energy Lab.(NREL), Golden, CO (United States).

San Joaquin Renewables. (2019, August 23). About San Joaquin Renewables. Retrieved from https://sjrgas.com/about-san-joaquin-renewables/.

SoCalGas. (n.d.). Biogas and Renewable Natural Gas: SoCalGas. Retrieved December 4, 2019, from https://www.socalgas.com/smart-energy/renewable-gas/biogas-and-renewable-natural-gas.

S.B. 1440, Energy: biomethane: biomethane procurement.(Ca. 2018). https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=201720180SB1440

Product: Fischer - Tropsch Fuels

Product Description

Fischer-Tropsch fuels are derived from biomass through gasification, gas cleaning, and catalytic treatment. Solid biomass is first gasified in oxygen and steam, with subsequent gas conditioning that includes cleaning of the raw synthesis gas and in some cases adjusting the composition of the syngas in preparation for downstream synthesis of Fischer-Tropsch liquids (FTL). Prior to synthesis, CO2 and sulfur compounds are removed in the acid gas removal step. The CO2 may be vented or captured and stored underground. Fischer-tropsch liquids typically contain a mixture of hydrocarbons, including gasoline and diesel substitutes (Kreutz, 2008).

Existing Capacity

Red Rocks Biofuels has proposed a facility in Lakeview, Oregon in part to serve California markets. This facility will consume 68,000 BDT/yr of biomass to produce 7.2 million gallons a year of jet fuel, 7.2 million gallons a year of diesel fuel, and 3.6 million gallons a year of naphtha (Red Rock Biofuels, 2018). This facility has not yet been placed in service.

Velocys plans on taking woody biomass forest residue from lumber industries and convert using proprietary Fischer Tropsch processes into aviation or heavy duty road transportation fuels. Of particular interest is Velocys integration of carbon capture utilization and storage (CCUS) technology into the process. Generating net negative carbon intensity fuels (Stratmann, 2019).

Justification

Among low-carbon transportation fuels, the production of FTL from lignocellulosic biomass has been given considerable attention. FTL offers logistical advantages over other biomass-derived fuels, including: (i) it is an energy-dense liquid fuel, (ii) no significant transportation fuel infrastructure changes would be required for widespread use, (iii) it can accommodate more easily the wide range of biomass feedstocks that are likely to characterize the lignocellulosic biomass supply—because gasification-based processes tend to more tolerant of feedstock heterogeneity than biochemical processes (Kreutz, 2008).

Market Indicators

There is an active international market for low-carbon liquid fuels. California currently uses liquid hydrocarbon fuels in the vast majority of its nearly 30 million vehicles.

Barriers to FTL from biomass are primarily financial, rather than technical. Renewed commercial interest in these fuels has been driven, in part, by low-carbon fuels policy in the Western United States, including California's LCFS. The LCFS provides subsidies for low-carbon fuels derived from lignocellulosic biomass.

Barriers to product or process innovation and growth
FTL plants exhibit large economies of scale, which increases the minimum viable capital investment necessary to construct a commercial facility (Sanchez and Kammen, 2016). Compared to other low-carbon fuels facilities (e.g. RNG, lignocellulosic ethanol), FTL plants face considerably higher capital requirements.

Furthermore, large feedstock requirements can create challenges with respect to security of supply of forest biomass in California.

Research Gaps
Barriers to F-T fuels from biomass are primarily financial, rather than technical. Several market formation activities, such as identification of candidate facility locations or preliminary front end engineering and design (pre-FEED) studies, could contribute to technology scale up.

Product Substitution
FTL is a direct substitute for fossil-derived liquid transportation fuels, including gasoline and diesel. FTL is a hydrocarbon liquid mixture that can be separated into drop-in fuels replacements. California is a large producer and consumer of petroleum, consuming over 15 billion gallons of gasoline in 2015. (State of Ca, 2019)

Opportunities for JIWPI Influence

- Should Red Rocks Biofuels proposed facility overcome key technical and financial hurdles, the JIWPI could undertake market formation activities, including policy, finance, or technology incubation.

MATRIX EXPLANATION

- **Minimum feedstock required:** *68,000 BDT/yr.* Red Rocks Biofuels has proposed a facility in Lakeview, Oregon in part to serve California markets. This facility will consume 68,000 BDT/yr of biomass to produce 7.2 million gallons a year of jet fuel, 7.2 million gallons a year of diesel fuel, and 3.6 million gallons a year of naphtha (Red Rock Biofuels, 2019).
- **Carbon storage:** *Possible.* CO2 capture and sequestration (CCS) is achievable on high-purity streams of CO2 produced during F-T fuels synthesis (Sanchez and Kammen, 2016).
- **Technology readiness level:** *7.* There have been several successful demonstrations of fuels synthesis via gasification and fischer-tropsch conversion of woody biomass. Full-scale demonstration, including startup and testing, has not yet been completed.
- **Commercial readiness level:** *6-7.* A deep understanding of the target application and market (low-carbon fuels in California) has been achieved. Product design is complete. Supply, customer agreements, and regulatory compliance are in process.

- **Feedstock use:** *Non-merchantable wood.* All lignocellulosic biomass, including forest and agricultural wastes, can be used.
- **International markets**: *Yes.* There is an active international market for low-carbon liquid fuels.
- **Potential market size:** *Large.* California currently uses liquid hydrocarbon fuels in the vast majority of its nearly 30 million vehicles.
- **Research or analysis need:** *Medium*. Barriers to F-T fuels from biomass are primarily financial, rather than technical. Several market formation activities could contribute to technology scale up.
- **Can JIWPI influence outcomes?** *High*. Should Red Rocks Biofuels proposed facility overcome key technical and financial hurdles, the JIWPI could undertake market formation activities.

References
Sanchez, D. L., & Kammen, D. M. (2016). A commercialization strategy for carbon-negative energy. Nature Energy, 1, 15002.

Kreutz, T. G., Larson, E. D., Liu, G., & Williams, R. H. (2008, September). Fischer-Tropsch fuels from coal and biomass. In *25th annual international Pittsburgh coal conference* (Vol. 29, p. e2). Princeton University Pittsburg.

Red Rock Biofuels. (n.d.). Lakeview Site. Retrieved December 4, 2019, from https://www.redrockbio.com/lakeview-site.html.

Stratmann, P. (n.d.). From waste woody biomass to carbon negative transportation fuels via CCUS. Retrieved December 4, 2019, from http://www.biofuelsdigest.com/bdigest/2019/12/02/from-waste-woody-biomass-to-carbon-negative-transportation-fuels-via-ccus/.

California, S. of. (n.d.). Board of Equalization Home Page. Retrieved December 4, 2019, from http://www.boe.ca.gov/.

Product: Gas Fermentation for Fuels

Product Description
Low-carbon cellulosic ethanol can be produced from lignocellulosic biomass through gasification, gas cleaning, and gas fermentation. The resulting syngas from gasification and gas cleaning is converted into cellulosic ethanol using gas fermentation technologies. Gas fermentation typically employs engineered bacteria to biologically process syngas into ethanol.

Existing Capacity
Aemetis has proposed a facility in Riverbank, CA that will produce 12 million gallons per year of cellulosic ethanol from 133,000 BDT/yr of agricultical wood waste from orchards. This facility has successfully secured a USDA loan guarantee, a 20-year feedstock supply agreement,

and a 55-year land lease (Shaver, 2018). Aemetis plans to open the facility in 2020 and an integrated demonstration unit has operated for 120 days. Future expansion at 3 other locations would bring total production to 160 million gallons of cellulosic ethanol (Aemetis, 2019).

Justification
Cellulosic ethanol is a low-carbon liquid transportation fuel that can be produced from lignocellulosic biomass. However, traditional biological processes to produce ethanol from lignocellulosic biomass, such as pretreatment, enzymatic hydrolysis, and fermentation of sugars, are not presently commercial viable in the United States. Gas fermentation is an alternative process that has recently found commercial markets. Large-scale technology producers, such as LanzaTech, are actively exploring market development in California and elsewhere.

Market Indicators
There is an active international market for low-carbon liquid fuels. California currently uses liquid hydrocarbon fuels in the vast majority of its nearly 30 million vehicles. Renewed commercial interest in these fuels has been driven, in part, by low-carbon fuels policy in the Western United States, including California's LCFS. The LCFS provides subsidies for low-carbon fuels derived from lignocellulosic biomass.

Barriers to product or process innovation and growth
The primary barrier to growth of cellulosic ethanol from forest biomass via gas fermentation is the lack of a demonstration facility operating on woody biomass feedstocks.

Research Gaps
See 'Barriers' above

Product Substitution
Ethanol derived from biomass is a transportation fuel already consumed at large scale in the United States (>15 billion gallons / yr). It is primarily used in light-duty vehicles as a source of transportation energy, and fuel octane enhancement. California currently consumes 1 billion gallons/yr of ethanol, which could be made from ~11 million BDT/yr biomass.

Opportunities for JIWPI Influence
- Should the Aemetis Riverbank facility achieve commercial viability, the JIWPI could undertake market formation activities, including policy, finance, or technology incubation.

MATRIX EXPLANATION
- **Minimum feedstock required:** *130,000 BDT/yr.* Aemetis, Inc is constructing a commercial scale facility producing 12 million gallons of ethanol per year from waste agricultural biomass in Riverbank, CA. (Shaver, 2018).
- **Carbon storage:** *No.* Cellulosic ethanol derived from gas fermentation is a low-carbon fuel.
- **Technology readiness level:** *8*. Gas fermentation to produce ethanol is proven at a commercial scale, but not using woody biomass as a feedstock. Aemetis, Inc has

successfully built and operated an integrated demonstration unit in California, and is constructing a full-scale facility in California operating on waste agricultural woody biomass (Aemetis, 2019).

- **Commercial readiness level:** *6*. A deep understanding of the target application and market (low-carbon fuels in California) has been achieved. However, we are not aware of any companies developing a facility in California that operates on forest woody biomass.
- **Feedstock use:** *Non-merchantable wood.* All lignocellulosic biomass, including forest and agricultural wastes, can be used.
- **International markets**: *Yes.* LanzaTech has developed several commercial gas fermentation facilities in international markets.
- **Potential market size:** *Large.* California currently consumes 1 billion gallons/yr of ethanol, which could be made from ~11 million BDT/yr biomass.
- **Research or analysis need:** *Medium*. JIWPI could perform market facilitation for gas fermentation processes operating on forest biomass.
- **Can JIWPI influence outcomes?** *Medium*. Should the Aemetis Riverbank facility be successful, JIWPI could commercialize this process using forest biomass.

References

Shaver, K. (2018, March 6). Aemetis Completes Operation of Cellulosic Ethanol Integrated Demonstration Unit, Produced Record Yields. Retrieved from http://www.aemetis.com/aemetis-completes-operation-of-cellulosic-ethanol-integrated-demonstration-unit-produced-record-yields/.

Aemetis. (2019). *Commercializing Below Zero Carbon Advanced Biofuels Production.* Retrieved from http://www.aemetis.com/wp-content/uploads/2019/01/Aemetis-Corporate-Presentation-2019-01-18.pdf

Product: Transportation fuels via fast pyrolysis and hydroprocessing

Product Description

Fast pyrolysis and upgrading is a thermochemical pathway that produces pyrolysis oil that can be upgraded via hydroprocessing into hydrocarbon-based transportation fuels.

This process includes fast pyrolysis of biomass at high temperatures, decomposing biomass feedstock into gas (syngas), solid (char), and liquid (pyrolysis oil) products. Pyrolysis oil is a viscous, oxygenated, and corrosive mixture of polymeric chemical compounds that has little immediate commercial value. Pyrolysis oil must be upgraded via a combination of hydrotreating and either hydrocracking or fluid catalytic cracking before high-value biobased hydrocarbons can be derived from it. Char can serve as a low-value coal substitute, soil amendment agent, or used for long-term carbon sequestration.

Existing Capacity
Lawrence Livermore National Laboratory, Sierra Pacific Industries (SPI), and Frontline Bionergy are in the process of testing a 50 ton per day autothermal pyrolysis unit operating on forest biomass at SPI's Camino mill in El Dorado County, CA (McCoy, 2018). The project is supported by the California Energy Commission.

Justification
Biobased hydrocarbons produced via fast pyrolysis and upgrading can be blended into fuels commonly known as "drop-in biofuels" due to their chemical similarity to petroleum-based fuels such as gasoline and diesel. Indistinguishable from their petroleum-based counterparts, these biobased hydrocarbons can be used to create a variety of products that have heretofore been the sole domain of the petroleum industry. While several pathways within the biochemical and thermochemical routes exist for the production of biobased hydrocarbons, fast pyrolysis is an economically attractive option (Brown, 2013)(Anex, 2010).

Market Indicators
There is an active international market for low-carbon liquid fuels. California currently uses liquid hydrocarbon fuels in the vast majority of its nearly 30 million vehicles. Renewed commercial interest in these fuels has been driven, in part, by low-carbon fuels policy in the Western United States, including California's LCFS. The LCFS provides subsidies for low-carbon fuels derived from lignocellulosic biomass.

Barriers to product or process innovation and growth
Processes for upgrading pyrolysis oil require substantial quantities of hydrogen and existing analyses of the pyrolysis oil upgrading and refining processes highlight the impact that hydrogen procurement strategy has on the project's economic feasibility. Producers may encounter high should upgrading occur at existing oil refineries.

The other primary barrier to growth of transportation fuels from forest biomass via fast pyrolysis and hydroprocessing is the lack of a demonstration facility operating on woody biomass feedstocks.

Research Gaps
See 'Barriers' above

Product Substitution
Transportation fuels produced by this process are a direct substitute for fossil-derived liquid transportation fuels, including gasoline and diesel. California is a large producer and consumer of petroleum, consuming over 15 billion gallons of gasoline in 2015.

Opportunities for JIWPI Influence
- Should the current pilot-scale facilities produce promising results, the JIWPI could undertake market formation activities, including policy, finance, or technology incubation.

MATRIX EXPLANATION

- **Minimum feedstock required:** *300,000 BDT/yr*. Prior process engineering studies have focused on a autothermal pyrolysis at the scale of 2000 tons biomass / day, producing 57 million gallons per year of transportation fuel (Brown, 2013).
- **Carbon storage:** *Yes.* Autothermal fast pyrolysis can produce recalcitrant biochar byproduct, contributing to carbon storage.
- **Technology readiness level:** *6.* Pilot-scale prototype system is being demonstrated in a relevant environment.
- **Commercial readiness level:** *5.* A deep understanding of the target application and market (low-carbon fuels in California) has been achieved. Lawrence Livermore National Laboratory, Sierra Pacific Industries (SPI), and Frontline Bionergy are in the process of testing a 50 ton per day autothermal pyrolysis unit operating on forest biomass at SPI's Camino mill in El Dorado County, CA.
- **Feedstock use:** *Non-merchantable wood.* All lignocellulosic biomass, including forest and agricultural wastes, can be used.
- **International markets:** *Yes.* There is an active international market for low-carbon liquid fuels.
- **Potential market size:** *Large.* California currently uses liquid hydrocarbon fuels in the vast majority of its nearly 30 million vehicles.
- **Research or analysis need:** *Medium*. JIWPI could perform market facilitation for bio-oil and hydrotreatment processes operating on forest biomass.
- **Can JIWPI influence outcomes?** *Medium.* Should existing pilot-scale facilities produce promising results, the JIWPI could undertake market formation activities.

References

Brown, T. R., Thilakaratne, R., Brown, R. C., & Hu, G. (2013). Techno-economic analysis of biomass to transportation fuels and electricity via fast pyrolysis and hydroprocessing. *Fuel*, *106*, 463-469.

Anex, R. P., Aden, A., Kazi, F.K., Fortman, J., Swanson, R.M., Wright, M.M., Satrio, J.A., Brown, R.C., Daugaard, D.E., Platon, A., Kothandaraman, G., Hsu, D.D., and Dutta, A. (2010). "Techno-economic comparison of biomass-to-transportation fuels via pyrolysis, gasification, and biochemical pathways." Fuel Techno-economic Comparison of Biomass-to-Biofuels Pathways 89(Supplement 1), S29-S35.

McCoy, S. (2018). Wood-to-fuel for California's Transportation Sector using Autothermal Pyrolysis [Powerpoint Slides]. Retrieved from http://sofarcohesivestrategy.org/wp-content/uploads/2017/06/McCoy-Wood-to-Fuel-pilot.pdf

Product: Lignocellulosic Ethanol

MATRIX EXPLANATION

- **Minimum feedstock required:** *100,000 BDT/Year*. Axens and Anderson Biomass have proposed an ethanol facility that will consume 100,000 BDT / yr when operating at capacity in Anderson, CA (cite).

- **Carbon storage:** *No.* Cellulosic ethanol is a low-carbon transportation fuel.
- **Technology readiness level:** *8.* Several commercial scale facilities exist that process non-forest based woody biomass, such as corn stover. Research into conversion of woody biomass feedstock is still needed to support commercial-scale production.
- **Commercial readiness level:** *6*. A deep understanding of the target application and market (low-carbon fuels in California) has been achieved. Anderson and Axens are currently developing supply agreements, CEQA permitting, and front end engineering and design.
- **Feedstock use:** *Non-merchantable wood.* Limited technical studies (Fagernas et al,. 2015, Theapparat et al., 2018) cite the use of small-diameter woody biomass as suitable for production, but the majority utilize other sources of biomass.
- **International markets**: *Yes.* There is an active international market for low-carbon liquid fuels.
- **Potential market size:** *Large.* California currently consumes 1 billion gallons/yr of ethanol, which could be made from ~10 million BDT/yr biomass.
- **Research or analysis need:** *High*. Research into conversion of woody biomass feedstock is still needed to support commercial-scale production.
- **Can JIWPI influence outcomes?** *Low.* We do not expect that the JIWPI will undertake research into woody biomass conversion. However, JIWPI could undertake market formation activities, as they could for other wood-derived fuels.

Product Description

Ethanol derived from forest biomass is a second generation cellulosic biofuel that can be used as a transportation fuel. Production generally occurs in the following steps:

1. Size reduction and pretreatment to increase the porosity of biomass particles and to increase the accessibility of cellulose and other polysaccharides to enzymes
2. Hydrolysis to produce sugars, typically catalyzed by enzymes that can collectively hydrolyze cellulose and hemicellulose to free sugars
3. Fermentation of sugars to ethanol, typically by yeast

Several pioneer facilities producing ethanol from lignocellulosic agricultural residues with capacity >10 million gallons per year have been built over the last few years. These include facilities in both Kansas and Iowa (Carroll, 2009).

Existing Capacity

Currently, there are no commercial scale facilities producing bioethanol in California. The proposed Axens/Anderson project will utilize the existing infrastructure at the Anderson, Ca complex. The facility will be capable of processing 100,000 BDT of feedstock per year.

Justification

Cellulosic ethanol is a low-carbon liquid transportation fuel that can be produced from lignocellulosic biomass.

Market Indicators

There is an active international market for low-carbon liquid fuels. California currently uses liquid hydrocarbon fuels in the vast majority of its nearly 30 million vehicles. Renewed commercial interest in these fuels has been driven, in part, by low-carbon fuels policy in the Western United States, including California's LCFS. The LCFS provides subsidies for low-carbon fuels derived from lignocellulosic biomass.

Barriers to product or process innovation and growth
Barriers to lignocellulosic ethanol production from agricultural biomass are primarily financial, rather than technical. A lack of commercially available processes for pretreatment and hydrolysis of woody biomass is also a large barrier, as explained below

Research Gaps
The major differences between woody and agricultural biomass are their physical properties and chemical compositions. Woody biomass is larger, stronger and denser, and has higher lignin content than agricultural biomass. As a result, woody biomass is more recalcitrant to microbial and enzymatic actions than non woody biomass. This is particularly true for softwood species (Zhu, 2010). Particular attention needs to be paid to (1) the effectiveness of pretreatment for complete wood cellulose saccharification and (2) the energy consumption for woody biomass pretreatment, in particular for wood-size reduction to the level for effective enzymatic saccharification.

Further, existing cellulosic biorefineries producing ethanol face economic barriers (Lynd, 2017). High capital costs are an impediment to the cost-competitiveness and replication of pioneer cellulosic biofuels facilities. For example, while the capital cost per annual gallon of capacity averages $13.81 / annual gallon for the first six commercial-scale lignocellulosic ethanol facilities; the corresponding value for corn ethanol plants is on the order of $2/gallon.

Product Substitution
Ethanol derived from biomass is a transportation fuel already consumed at large scale in the United States (>15 billion gallons / yr). It is primarily used in light-duty vehicles as a source of transportation energy, and fuel octane enhancement. California currently consumes 1 billion gallons/yr of ethanol, which could be made from ~11 million BDT/yr biomass.

Opportunities for JIWPI Influence

- Evaluation of whether ligno cellullosic ethanol processes developed for agricultural biomass are amenable to California softwood species. We do not expect that the JIWPI will undertake research into woody biomass pretreatment and conversion in the near-term.
- However, JIWPI could undertake market formation activities, as they could for other wood-derived fuels.

References
Spyridon, A., Euverink, W., & Jan, G. (2016). Consolidated briefing of biochemical ethanol production from lignocellulosic biomass. *Electronic Journal of Biotechnology*, *19*(5), 44-53.

Zhu, J. Y., & Pan, X. J. (2010). Woody biomass pretreatment for cellulosic ethanol production: technology and energy consumption evaluation. *Bioresource technology*, *101*(13), 4992-5002.

Lynd, L. R., Liang, X., Biddy, M. J., Allee, A., Cai, H., Foust, T., ... & Wyman, C. E. (2017). Cellulosic ethanol: status and innovation. *Current opinion in biotechnology*, *45*, 202-211.

Carroll, A., & Somerville, C. (2009). Cellulosic biofuels. *Annual review of plant biology*, *60*, 165-182.

https://www.alliedmarketresearch.com/bioethanol-market