BioBased Maine: Advancing Sustainable Manufacturing

Renewable Chemicals Study Findings

November 30, 2017

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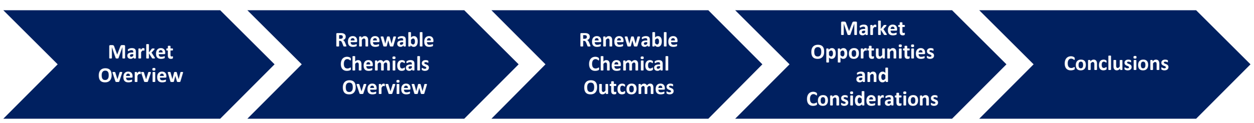
EXECUTIVE SUMMARY

Ascendant Partners, Inc. ("Ascendant") was engaged by Environmental Health Strategy Center ("EHSC" or the "Company") under a Federal Grant as a consultant to the Company in connection with the preparation and delivery of the Biobased Chemical Market Analysis. Through this study, Ascendant sought to provide an independent perspective to help identify, understand, and present key opportunities for EHSC in the biobased chemical market and potential factors affecting the viability and sustainability of the production of various biobased chemicals analyzed.

Ascendant used a combination of primary research through interviews with technology providers and other industry participants and secondary research utilizing company websites and research reports. The outcomes of this research have been compiled and presented to provide EHSC and BioBased Maine the necessary information to identify potential global markets for cellulosic sugars, biobased platform chemicals, and other biobased chemicals that can be manufactured from Maine's lignocellulosic biomass.



Market Overview

The industry of biobased products is broad and many segments are intermingled. Additionally, many biobased product markets are not fully mature. The stage of development in the various biobased products ranges from research to early development and from the path towards commercialization to adoption by the marketplace or to market maturity.

While the industry continues to emerge, best practices and processes are evolving to allow the industry to grow and compete in a highly competitive and mature industry with a stalwart of entrenched competitors. Despite past challenges and future hurdles, the industry, led by government policy and research, is moving forward with developing fuel and chemical technologies. In addition, strong cooperation within the value chain from feedstock producer to end user is required for new biobased chemicals to successfully enter the market. The value chain can be driven by technology push, market pull or both. Since biobased chemicals are marketed from business to business, the key decision-makers in the value chain can be either chemical companies or brand owners.

Renewable Chemicals Overview

Ascendant sought to provide a current state of the biobased chemical market by focusing on chemicals with either existing markets or future potential markets. Our initial starting point was the 2004 Department of Energy's list of "Top Value Added Chemicals from Biomass." The list of building blocks was a great starting point but much has changed in the bioeconomy in the last 13 years. From this initial list, we gathered insight from industry experts on qualities that are important for biochemicals to be successful in the market today and in the future. We gathered four critical success factors from our conversations to narrow down the original building blocks to those relevant today and to widen our search for new chemicals that have garnered attention lately.

- Is it a platform chemical?
- Does it contain an oxygen molecule?
- Does it compete directly with a product from petroleum or natural gas?
- Is there significant market interest?

These factors combined with our research and interviews resulted in 11 chemicals that were profiled in this report: 1,4 Butanediol (BDO), Furans (Furfural, HMF, FDCA), Glucaric Acid, Isoprene, Itaconic Acid, Lactic Acid, Levulinic Acid, Para-xylene, 1,3 Propanediol (PDO), Succinic Acid, and Xylitol.

Renewable Chemical Outcomes

Ascendant assembled a ranking system to compare and contrast the profiled chemicals to filter the chemicals which warrant further analysis, continued interest, and should be watched closely as the industry continues to evolve. The ranking system is based on these same four success factors on a scale of green to red derived from insight gained in conversations with industry experts and were also used to derive our initial list.

After assessing the chemicals based on the success factor criteria, four chemicals came out more favorably than the rest: furans, lactic acid, succinic acid, and xylitol. All four chemicals include oxygen as a molecule and ranked highly in the other areas as described in the table below.

	Flexibility in Products/Pathways (Platform Chemical)	Product/Derivative Competition with Petroleum Products	Extent of Commercialization and Market Interest
Furans	Furfural has various derivatives and uses, mostly as a solvent. HMF has one derivative in FDCA which is primarily used as a replacement of terephthalic acid to create PEF	Furans can't be made from petroleum processes. FDCA is a functional replacement for terephthalic acid to make a new polyster in PEF	Furfural and HMF are small markets, with the majority of interest coming from FDCA. Companies that use PET bottle like Coca-Cola and Danone have significant interest in PEF bottles
Lactic Acid	Lactic Acid has direct uses but its potential as a bio-product is dependent on PLA	Lactic acid is only made form renewable processes and PLA is a novel product with different properties than other plastics	PLA has garnered plenty of interest from retailers to meet sustainability goals since it is biodegradable. Commercialization is being pursued by 3 prominent producers
Succinic Acid	Succinic acid has many uses and derivatives in industrial, pharmaceutical, food, and other industries. It is the prime example of a platform chemical	Succinic acid is a direct competitor with petroleum products as is its derivative BDO. It also acts as a functional replacement to adipic acid	Succinic acid has been a hot story in the bioeconomy. 4 companies with prominent investors pursued commercialization at the same time
Xylitol	Xylitol has uses in food, odontological, and pharmaceutical markets. However, its primary market is as a "sugar free" substitute for gum and candy	Xylitol can only be made from renewable sources and does not compete with petroleum products. However; it does compete with commodity sugars.	Xylitol has gained interest as a sugar substitute and is produced by DuPont Danisco. S2G Biochem is also pursuing commercialization by building a plant in the Sarnia Bio-cluster

Other chemicals are interesting to watch going forward also such as para-xylene, which has generated tremendous market and technology interest, and levulinic acid that has intriguing potential products in early stage markets.

Market Opportunities and Considerations

Stakeholders in Maine's $8.5B industry and around the pulp and paper global market are looking to increase value in their existing infrastructure. In order to remain viable, many are exploring increasing value by producing bioenergy and biomaterial along with the wood, pulp, and paper products as a path forward.

The business model that has been proposed is the forestry biorefinery. A biorefinery is defined by IEA Bioenergy Task 42 as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)". The concept is comparable to the petroleum refinery model which produces multiple fuels, chemicals, and other products from petroleum utilizing the scale and infrastructure for improved economics. Although the concept has been explored for awhile and certain facilities may fit the description, the biorefinery model has not been completely realized.

Ascendant looked at three biorefineries that are in process today as case studies including the Lenzing Biorefinery in Lenzing, Austria, the UPM Lappeenranta Biorefinery in Lappeenranta, Finland, and the Sarnia-Lambton Biohybrid Chemistry Cluster in Ontario. In examining biorefinery scenarios and speaking with stakeholders in Sarnia, Ascendant has compiled the following lessons and associated best practices.

Lessons Learned	Best Practices
It is beneficial to "grow green" around the commodity infrastructure, not compete with it	The existing infrastructure is in place because of the commodity process. Make sure renewable processes fit as seamless as possible without disrupting the commodity operations
Marketing for the opportunity is very important to attract investment and technology companies	The region's image can be a strong marketing tool. Start the marketing campaign early and seek professional marketing support
All parts of the community must be aligned 100% towards the same goal (incl. rural community, government, and business)	Ensure that all parties are consulted and will benefit from project from early stage to help attract positive attention, momentum, and ultimately investment
Flexible biorefineries which produce high value products and utilize most of the biomass are important for profitability	Utilize multi-product streams, focus on technology with high biomass utilization, and emphasize high value products early
Increased production of one product decreases production of another	Look at local economics of all products and plan contractual agreements for changing environments
Many unforeseen problems arise during scale-up of a technology	Emphasis should be placed on risks of scale-up; data validation and pilot stage performance should be scrutinized prior to design of integrated project

Conclusions

Through the study, the common theme was that the markets are still developing and the companies are still developing technology to pursue various pathways. It remains to be seen what technologies and chemicals will ultimately be a success in the long term. The successful renewable chemicals require a balance of production, market size, and selling price.

In our conversations with industry stakeholders, we picked up valuable insight into approaches to consider when designing a business model and evaluating how to integrate the infrastructure with biobased technologies.

- The renewable chemical technologies should start with the end markets in mind. The pathways should be determined by what the market wants in terms of products and exact specifications.

- A platform chemical allows a business to build a business plan around a niche market to sustain in the short term and expand into larger volume markets as the process is streamlined and scale-up is achieved.

- The process technology should be able to fit seamlessly with the existing commodity infrastructure.

Maine should continue to develop criteria based on the starting points that Ascendant has laid out to find the right biochemical technology and business model to match with Maine's infrastructure. A narrower focus and criteria when monitoring the biobased chemical market will allow Maine to act if the markets and technology reach defined critical milestones.

MARKET OVERVIEW

Introduction

The market for biobased chemicals, like most of the biobased industry, is still evolving and creating opportunities to compete against incumbent products currently made from petroleum and conventional sugar sources. Biobased chemicals provide many promising opportunities due to their chemical structure that allows for new applications or replacement of existing chemicals. The industry of biobased products is broad and many segments are intermingled. Additionally, many biobased product markets are not fully mature. The stage of development in the various biobased products ranges from research to early development and from the path towards commercialization to adoption by the marketplace or to market maturity.

Broadly speaking the industry generally defines the biobased chemical as drop-in or novel biobased chemicals.

- Drop-in chemicals are bio-based versions of existing petrochemicals which have established markets. They are chemically identically to their hydrocarbon counterparts and have lower financial and technology risk and can promote faster market access for producers.
- Novel bio-based chemicals have greater financial and technology risks for producers, but can be used to produce products that cannot be obtained from traditional production techniques. Products created from these chemicals may offer unique or superior properties relative to existing petroleum-based chemicals. These products may allow them to be functional replacements for existing petrochemicals also, where they can be used for the same purpose but have different properties.

In general, a biobased chemical, whether a "drop in" or novel, can be described as a "platform chemical" if it has the ability to be used in multiple downstream chemical pathways by changing the initial chemical structure. This provides a level of robustness that may allow producers to better absorb market and cost fluctuations compared to a chemical with a single pathway.

Currently and in the near term, grains will be one of the primary feedstocks for biobased product production, with corn being the primary feedstock. However, for biobased products and biofuels to achieve industry targets, developing alternative feedstocks such as cellulosic biomass will be required. Integrated biorefineries may provide further benefits for production of biobased chemicals including overall economics and sustainability while reducing U.S. dependence on imported oil and improving the economic outlook of declining industries such as pulp and paper.

Industry Overview

Production of biobased chemicals has been primarily influenced by downstream participants and existing biotechnology and chemcial companies such as Cargill and DuPont, for example.

Current and Planned Bioproduct Facilities in the US

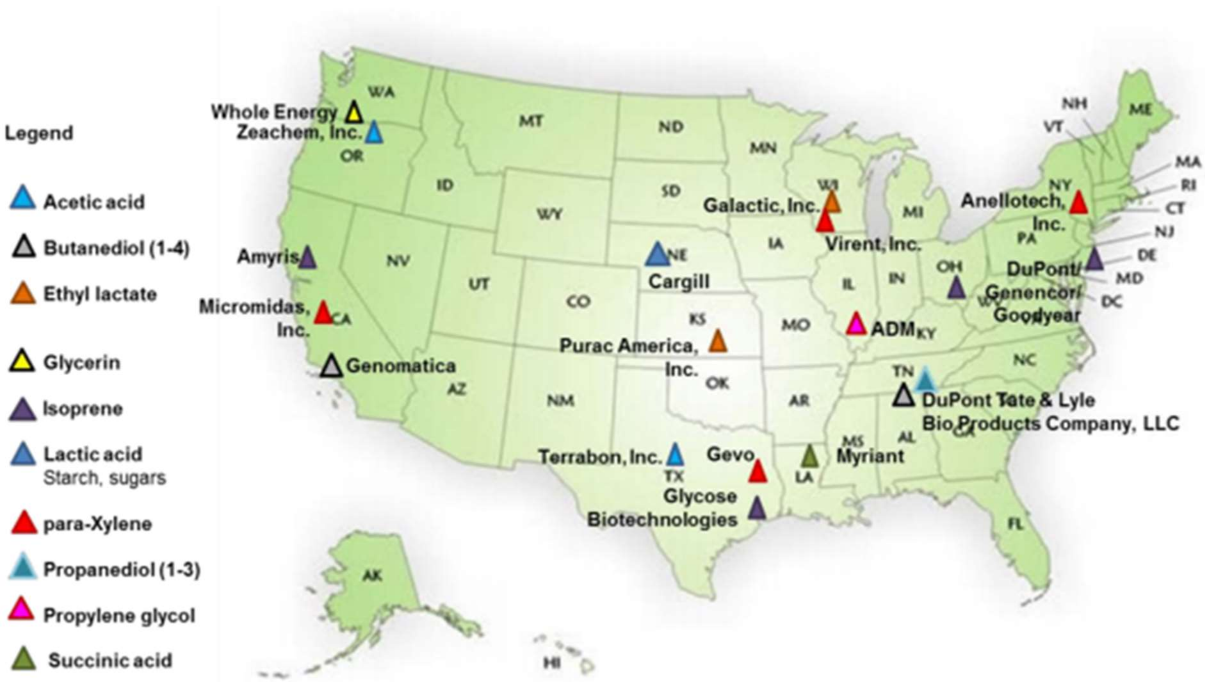


Figure 1: Current and Planned Bioproduct Facilities in the US[1]

The production of chemicals from biomass has gained increasing interest over the last decade in response to higher costs of processing cellulosic biomass. Specialty or niche chemical markets afford the cellulosic biomass processor the opportunity for higher selling prices that are able to better absorb potentially higher production costs. Because they are more oxygenated, biomass feedstocks have an advantage over petroleum feedstocks because many chemical products are functionally more similar to biomass than petroleum feedstocks.

[1] Source: NREL, "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential"

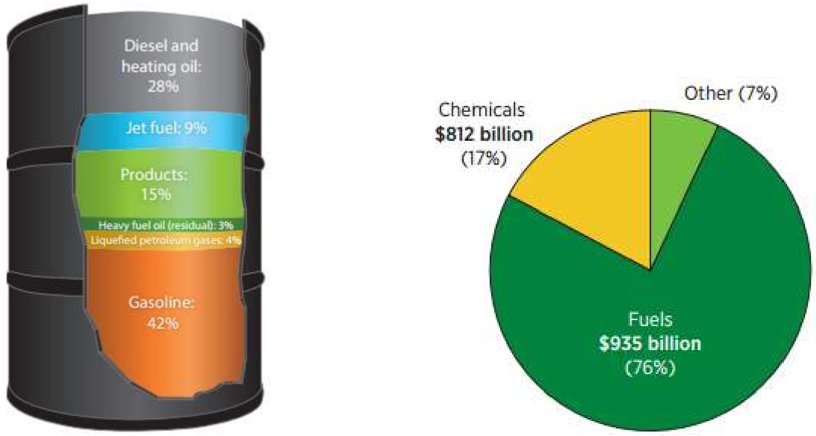


Figure 2: Products from a barrel of crude oil and Annual Revenues[2]

In considering petroleum refinery economics, 15% of the entire barrel of oil goes toward the production of chemical products, while chemical products account for nearly 50% of the profits. This point illustrates, the margin potential available in chemical production and the relatively small amount of overall oil that is used for chemical production in the petroleum industry. Chemical production also has a big impact on the overall sustainability of a refinery process. According to recent International Energy Agency reports, the chemicals industry accounts for 30% of the total industrial energy demand worldwide and is responsible for 20% of the industrial greenhouse gas emissions[3].

Emerging bioproducts are active subjects of research and development which have been driven by the price of traditional petroleum-based products, the environmental impact of petroleum use, and an interest in becoming more independent from foreign oil. Bioproducts derived from biomass can replace (either directly or indirectly) some of the fuels, chemicals, plastics, etc., that are currently derived from petroleum. Examples include bioadhesives, biopolymers, and biochemicals and can enable the production of bioenergy, either as co-products to improve the economics of the primary fuel product in an integrated biorefinery, or as enablers in developing technologies and processes essential to the long-term production of biofuels and bioenergy.

[2] Source: BETO Strategic Plan
[3] Source: IEA, "Technology Roadmap Energy and GHG Reductions in the Chemical Industry via Catalytic Processes"

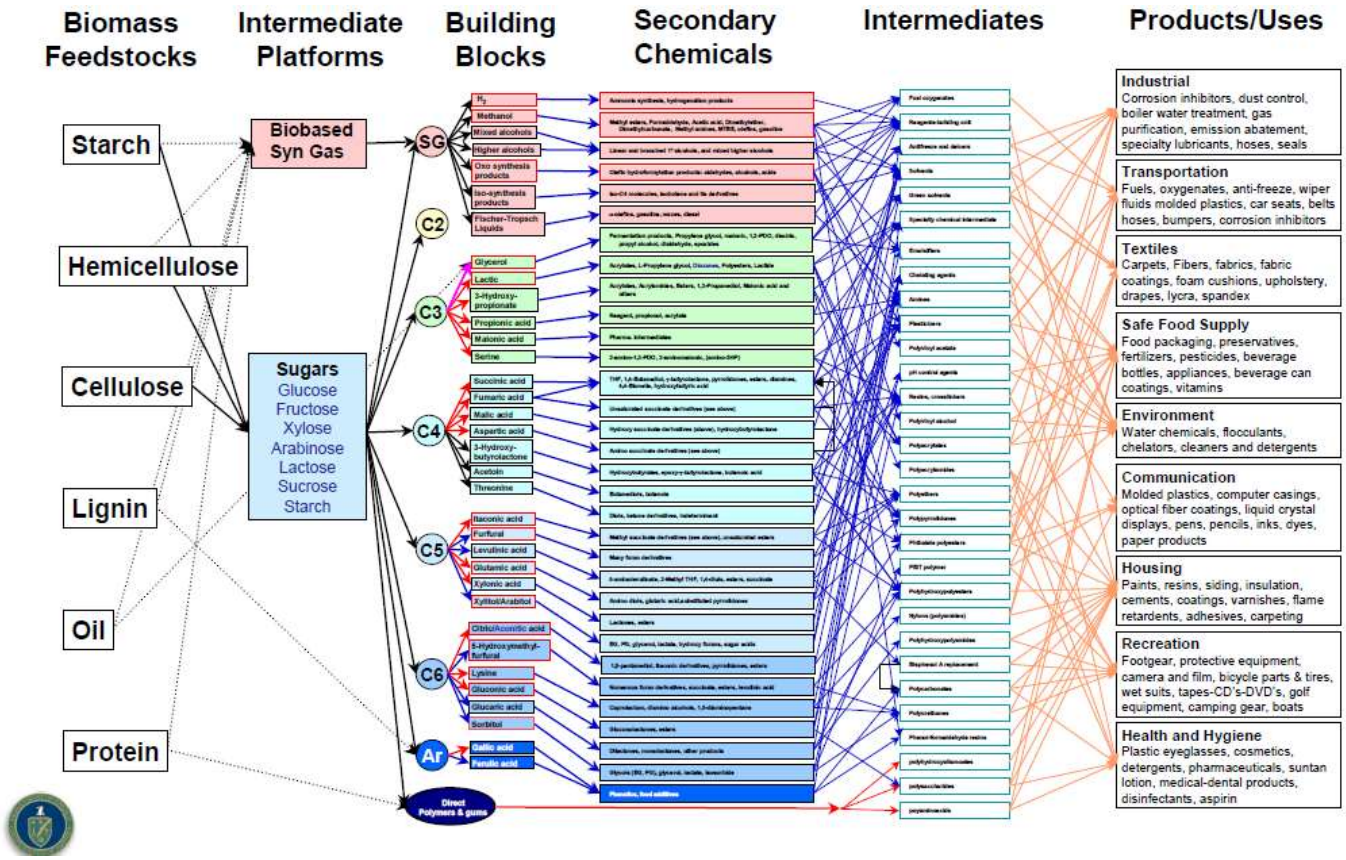


Figure 3: Analogous Model of a Biobased Product Flow-chart for Biomass Feedstocks[4]

As illustrated in Figure 3, the production of sugars from cellulosic sources provides an overwhelming number of chemical pathway options that have many applications and uses and often overlapping pathways for the various applications. Many in the industry have sought to refine and develop a cohesive roadmap for successful biobased chemical integration, but, ultimately, the most promising chemicals and pathways is still being determined by industry and academia.

In 2004, the US DOE released an often-cited report that identifies the top value-added chemicals from biomass. In this report, the author rigorously reviewed the chemicals market to determine the 12 most promising sugar-derived chemicals and materials that could serve as economic drivers in a biorefinery. These chemicals are the building blocks for numerous secondary chemicals and intermediates that are used across all industries.

[4] Source: US DOE EERE: Top Value Added Chemicals from Biomass

Building Blocks
1,4 succinic, fumaric and malic acids
2,5 furan dicarboxylic acid
3 hydroxy propionic acid
aspartic acid
glucaric acid
glutamic acid
itaconic acid
levulinic acid
3-hydroxybutyrolactone
glycerol
sorbitol
xylitol/arabinitol

Figure 4: DOE: Top Value Added Chemicals from Biomass[5]

Building block chemicals are molecules with multiple functional groups that possess the potential to be transformed into new families of useful molecules. The twelve sugar-based building blocks are 1,4-diacids (succinic, fumaric and malic), 2,5-furan dicarboxylic acid, 3-hydroxy propionic acid, aspartic acid, glucaric acid, glutamic acid, itaconic acid, levulinic acid, 3-hydroxybutyrolactone, glycerol, sorbitol, and xylitol/arabinitol. Since the initial work in 2004, many in the industry have continued to refine the initial 12 building blocks and modify the list as more information and developments are discovered.

Prices vary widely in the chemicals market and are dictated by end market applications and demand, availability of supply, and oil prices. As a key determinant of profitability, it is important to understand chemical prices and their variability. While a chemical may have a high price point, variability in price may make it an unattractive chemical for biobased production and indicative of a product that can be produced cheaply through traditional processes or small market size.

[5] Source: US DOE EERE: Top Value Added Chemicals from Biomass

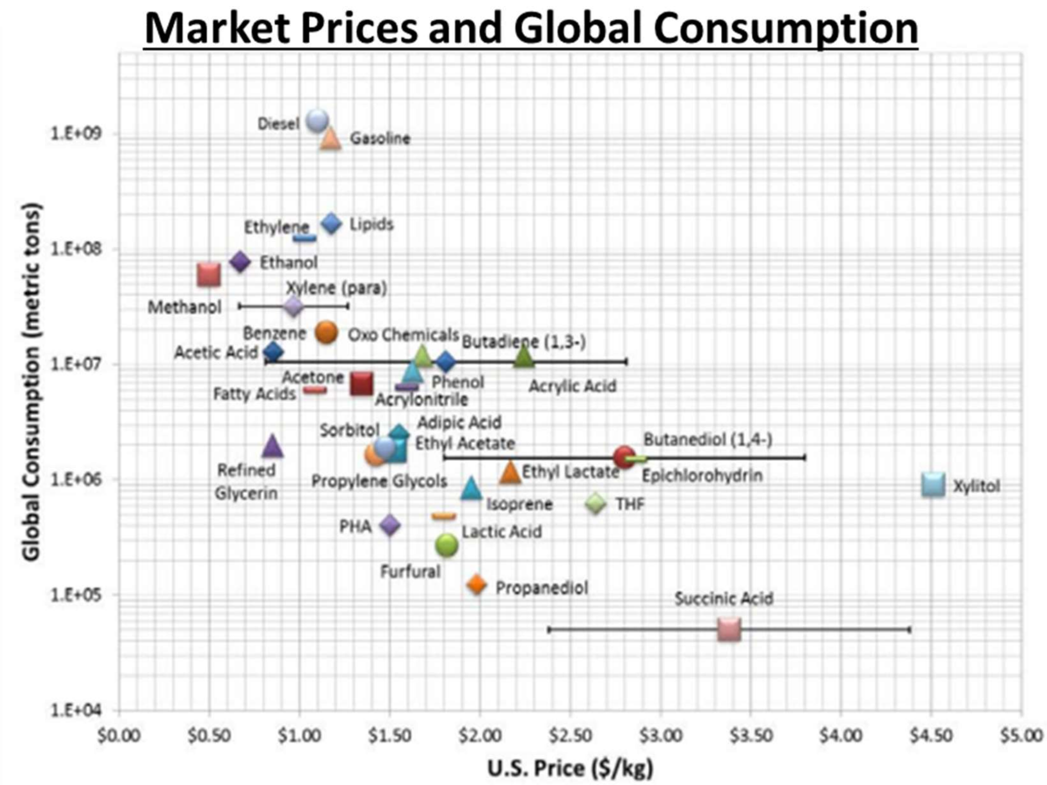


Figure 5: Chemical Pricing and Global Demand[6]

The figure above shows the 3-5 year average for various chemicals and error bars for chemicals with large price fluctuations. Most chemicals had a standard deviation of $0.30/kg or less. A promising point to note is that many of these products have values much greater than gasoline or diesel fuel products. A challenge with these single-point assessments, however, is that these are inherently commodity markets, with prices and consumer demands that fluctuate. Conversely, biobased alternatives that are able to overcome the volatility driven nature of their petroleum-based counterparts will likely have greater adoption as could increase overall consumption as users adopt a less volatile biobased chemical solution.

Industry Outlook

Several recent studies have been completed showing the current size of the biobased chemicals market. The USDA completed a report in 2015 that analyzed the economic impact of the US bioproducts industry. In this report, the USDA estimated that direct sales of biobased products in 2013 totaled about $126 billion[7]. Importantly, this study included traditional based oleochemicals markets. In contrast to the 2015 USDA study, a second recent report only included renewable commodity chemicals, renewable polymers, and other materials produced from biomass that are not consumed as fuels. Also prepared by the USDA, this study estimated current production of 1.1 billion pounds of chemicals with a total value of $2.5

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[6] Source: NREL, Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

[7] Source: USDA: An Economic Impact Analysis of the U.S. Biobased Products Industry

billion[8]. Based on the market sizes for these products, the production value of $2.5 billion represents approximately 1-2% of the overall market.

USDA Chemical Market Projections, Total and Biobased, US$ Billions									
	2005			2010			2025		
	Total	Biobased	% of Total	Total	Biobased	% of Total	Total	Biobased	% of Total
Commodity	475	0.9	0.2%	550	5-11	1.5%	857	50-86	7.9%
Specialty	375	5	1.3%	435	87-110	22.6%	679	300-340	47.1%
Fine	100	15	15.0%	125	25-32	22.8%	195	88-98	47.7%
Polymer	250	0.3	0.1%	290	15-30	7.8%	452	45-90	14.9%
Total	**1,200**	**21.2**	**1.8%**	**1,400**	**132-183**	**11.3%**	**2,183**	**483-614**	**25.1%**

Figure 6: Projected Global Markets of Chemical Sectors: 2005, 2010, and 2025[9]

The USDA has also projected the use of biobased chemicals will increase through 2025 from 1.8% of total chemical sectors to 25% of all chemicals in 2025. Commodity chemicals are manufactured in very large volumes, typically more than 3 million tons per year, worldwide. Specialty chemicals are for special uses or intermediates, and are also produced in large volumes. Fine chemicals are manufactured in smaller batches and intended mainly for pharmaceutical intermediates, enzymes, flavors and fragrances, and polymers.

Biobased polymer and commodity chemicals are projected to increase the most amongst the chemicals projected by USDA and are projected to increase 225x and 76x from 2005, respectively. While all areas are projected to have strong growth, biobased polymers and commodity chemicals are higher due to their lower starting base. Biobased specialty and fine chemicals are projected to have the highest proportion of their total market with approximately 47% market share for each by 2025. New biobased chemicals and materials most likely will be concentrated in the fine chemicals sector and biotechnology's contribution to value in this segment will be driven by new revenue growth, as opposed to cost savings in the processing of existing products[10].

Another factor impacting the outlook for biobased chemical production is the rise and continued production in the US from shale gas resources. In addition to changing the supply of petroleum-based chemicals, shale gas production has served to lower global oil prices. The impact of lower prices disincentivized chemical producers to look for alternative to petroleum feedstocks causing producers to lose the urgency in adopting biobased alternatives.

[8] Source: USDA, Renewable Chemicals & Materials Opportunity Assessment
[9] Source: USDA, US Biobased Products Market Potential and Projections Through 2025
[10] Source: Ibid.

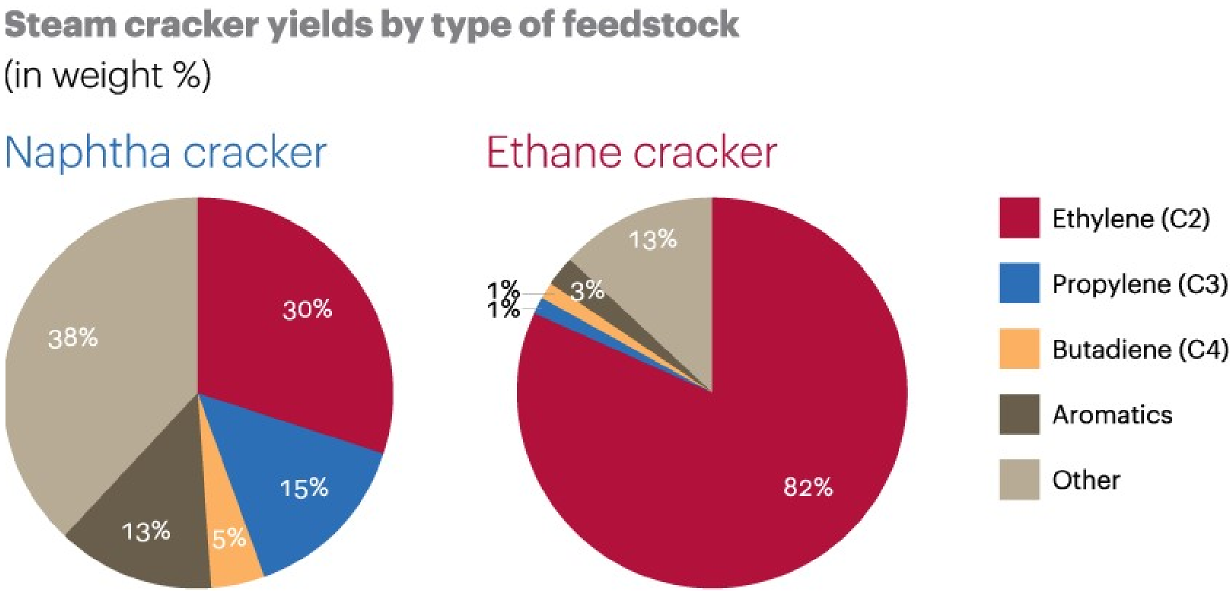

Figure 7: Olefin Yields by Feedstock[11]

As it relates to shale gas production, biobased chemicals could help replace the supply of aromatics or C_3 or C_4- building blocks lost to increasing shale gas production[12]. The shift towards ethane cracking as a result of shale gas production has reduced supplies of propylene and butadiene, two important petrochemical products and have opened a window of opportunity for biobased chemicals. Looking forward, shale gas production is likely to continue providing greater certainty for biobased chemical producers pursuing these product markets.

Renewable Chemicals Act of 2017

To help accelerate market adoption, the federal and state governments have adopted or proposed various laws that incentivize biobased chemical production. Most recently, a law was introduced at the federal level to provide a short-term tax credit.

The legislation, if enacted, would create a targeted, short-term tax credit for production of qualifying renewable chemicals from biomass or investment in production facilities. Applicants for the tax credit would be evaluated on job creation, innovation, environmental benefits, commercial viability and contribution to U.S. energy independence.

This bill amends the Internal Revenue Code to allow: (1) a business-related tax credit for the production of renewable chemicals, and (2) a tax credit for investment in renewable chemical production facilities.

The bill defines "renewable chemical" as any chemical that: (1) is produced in the United States from renewable biomass; (2) is sold or used for the production of chemical products, polymers, plastics, or formulated products or as chemicals, polymers, plastics, or formulated products; (3) has a biobased

[11] Source: A.T. Kearney, Shale Gas: Threat or Opportunity for the GCC?
[12] Source: BIO-TIC, Biobased Chemical Building Blocks Summary Report

content of not less than 95%; (4) is the product of, or reliant upon, biological or thermal conversion of renewable biomass; (5) is not sold or used for the production of any food, feed, or fuel; and (6) is not a chemical for which either of the tax credits established by this bill have been claimed by the taxpayer in any taxable year.

The bill requires the Department of the Treasury to establish a program to allocate renewable chemical tax credit amounts to eligible taxpayers and imposes an aggregate limit on the amount of credits that may be allocated to not more than $500 million during the 5-year period after enactment of this bill. The amount of the credits that may be allocated to any taxpayer for any taxable year may not exceed $25 million[13].

The bill still needs to make it ways through all levels of the government, but would be a positive development for the biobased chemicals industry if enacted. The senators who introduced this bill were also involved with a similar bill in 2015 that was not passed.

While the industry continues to emerge, best practices and processes are evolving to allow the industry to grow and compete in a highly competitive and mature industry with a stalwart of entrenched competitors. Despite past challenges and future hurdles, the industry, led by government policy and research, is moving forward with developing fuel and chemical technologies. In addition, strong cooperation within the value chain from feedstock producer to end user is required for new biobased chemicals to successfully enter the market. The value chain can be driven by technology push, market pull or both. Since biobased chemicals are marketed from business to business, the key decision-makers in the value chain can be either chemical companies or brand owners.

[13] Source: S.1980 - Renewable Chemicals Act of 2017

RENEWABLE CHEMICALS

Ascendant sought to provide a current state of the biobased chemical market by focusing on chemicals with either existing markets or future potential markets. Our initial starting point was the 2004 Department of Energy's list of "Top Value Added Chemicals from Biomass." This report influenced much of the interest in the bioeconomy over the last 13 years and technologies centered their processes around the qualities of these identified building blocks. The DOE paper by Joseph Bozell and Gene Petersen started with over 300 possible building block chemicals and then looked at cost of feedstock, processing costs, current market volume and prices, and relevance to current/future biorefinery operations. They further looked at whether a chemical was a direct replacement or a novel product, and whether it was a building block intermediate[14]. By using this criteria, they were able to narrow down their list to the building block chemicals mentioned previously. This list was a great starting point but much has changed in the bioeconomy in the last 13 years. Ascendant compiled the following table for the commercialization status of the building blocks to see which chemicals are most relevant to the current bioeconomy.

DOE's Building Blocks	Commercialization Status
Succinic, fumaric, and malic acids	Succinic acid has been a hot story in the bioeconomy. 4 companies with prominent investors pursued commercialization at the same time; Novozymes announced a process for malic acid in 2012 but news has been scarce since.; Myriant has fumaric acid in its development pipeline.
2,5 Furan dicarboxylic acid (FDCA)	FDCA has generated interest for its use in PET, especially by companies that use PET bottles like Coca-Cola and Danone.
3 Hydroxy propionic acid	Cargill has been the main player for 3-HPA. They bought OPX technologies' fermentation technology in 2015 and also announced a JV with Novozymes and BASF. BASF has since dropped out and no new news has come out since 2015.
Aspartic acid	Flexible Solutions announced their technology was producing aspartic acid from sugar at their Alberta facility in 2011. No press releases have come out since.
Glucaric acid	Rennovia and Johnson Matthey announced a collaboration in 2014 and added a licensing agreement with ADM in 2017. They have a demo plant in Stockton, England. Rivertop Renewables sold anti-corrosion products and detergents on the market before going bankrupt over the last year.
Glutamic acid	There is no recent news of companies pursuing commercialization of glutamic acid technologies. The Pacific Northwest National Laboratory has done studies in the past and the technology is available for license.
Itaconic acid	The majority of production comes from China, but Itaconix out of the UK, has an American office. They produce non-phosphate detergent builders, personal care polymers, and binders for paints.
Levulinic acid	Commercial production is limited to a few Chinese producers currently. Biofine Technology has a pilot plant in Maine, targeting ethyl levulinate and jet fuel. GFBiochemicals states they are producing product at their plant in Italy but this is unconfirmed. They also announced an upcoming biorefinery with American Process.
3-Hydroxybutyrolactone	There is no commercialization efforts taking place only studies in academic labs currently.
Glycerol	Glycerol production has been prevalent with the increase in biodiesel production. It has found uses in various industries and work is being done to explore derivatives such as propylene glycol.
Sorbitol	Sorbitol has uses in the market currently but there is no information of companies pursuing from lignocellulosic feedstocks.
Xylitol/arabinitol	Xylitol has gained interest as a sugar substitute and is produced by DuPont Danisco. S2G Biochem is also pursuing commercialization by building a plant in the Sarnia Bio-cluster.

Figure 8: Commercialization Status of the DOE's Building Blocks[15]

[14] Source: US DOE EERE: Top Value Added Chemicals from Biomass
[15] Source: Biofuels Digest

From this initial list, we gathered insight from industry experts on qualities that are important for biochemicals to be successful in the today's market and in the future. We gathered four critical success factors from our conversations to narrow down the original building blocks to those relevant today and to widen our search for new chemicals that have garnered attention lately. Those four success factors are:

- **Is it a platform chemical?**
- **Does it contain an oxygen molecule?**
- **Does it compete directly with a product from petroleum or natural gas?**
- **Is there significant market interest?**

These factors served to eliminate some of the original list and add other chemicals based on other industry papers. We placed the heaviest weighting on market interest starting with our commercialization table for the building blocks. The markets are not very transparent and technical viability is difficult to verify so efforts to commercialize and interest by prominent companies were the best indication of market potential. These factors resulted in the following 13 chemicals: 1,4 Butanediol (BDO), Furans (Furfural, HMF, FDCA), Glucaric Acid, Isoprene, Itaconic Acid, Lactic Acid, Levulinic Acid, Para-xylene, 1,3 Propanediol (PDO), Succinic Acid, and Xylitol.

There were two other chemicals that fit the criteria, ethanol and glycerol, that were considered but ultimately not included in the report. Ethanol was excluded because we focused on chemicals that had flexibility to go into less commoditized markets and cellulosic ethanol is cost prohibitive without the enhancement provided by government incentives. Also, the market has recently witnessed large-scale, unsuccessful cellulosic projects such as Kior and Abengoa. Bio-polyethylene and 1,3 butadiene were eliminated since their main renewable pathway is via ethanol. Glycerol and its derivative bio-propylene glycol were left out of the report because glycerol is a waste product of biodiesel production and did not apply when considering woody biomass.

1,4 – Butanediol (BDO)

BDO is a primary alcohol that has been identified as building block for polyesters, solvents, and chemicals. It has a large market and can be made from petroleum and renewable processes. Prominent companies such as Nike and Invista have shown interest in using bio-BDO in their spandex products[16]. BDO has a chemical composition of $C_4H_{10}0_2$.

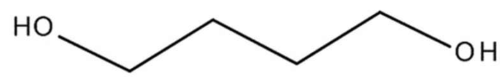

Figure 9: BDO Chemical Structure ($C_4H_{10}0_2$)[17]

<u>Chemical Synthesis Process</u>

1,4-BDO can be produced from numerous production methods and various feedstocks, as many if not more than other large-volume chemicals. The first industrial process for BDO was developed in the 1930's by German chemist Walter Reppe and is still the primary process used in the US and Western Europe. The Reppe process is a two-stage process that involves formaldehyde and acetylene being reacted to form 1,4-butynediol which is hydrogenated in subsequent stage to BDO[18].

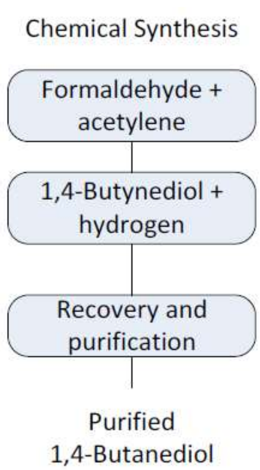

Figure 10: BDO Chemical Synthesis[19]

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[16] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[17] Source: www.sigmaaldrich.com
[18] Source: Plotkin, Jeffrey: The Many Lives of BDO
[19] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

Another process that is used for commercial production of BDO is the Davy process. During the Davy process, maleic anhydride is esterified to form di-methyl maleate intermediate ester which is hydrogenated to produce BDO, THF, and GBL. This technology was purchased by Johnson Matthey in 2006 for $70MM[20].

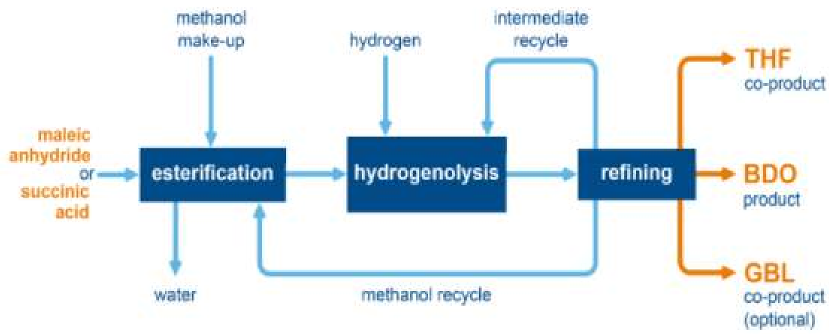

Figure 11: DAVY Process[21]

Other petroleum routes have been used from butadiene and acetic acid, propylene, and succinic acid.

Renewable Production Process

There are two main processes for BDO production from renewable material, direct fermentation and catalytic upgrading of intermediates. Genomatica has been the leader in pursuing the direct fermentation route from sugar to BDO[22]. Direct biological production was a challenge since BDO is not produced naturally by any known organisms. However, Genomatica announced in 2008 that they had engineered a strain of E. coli that can produce BDO from glucose, xylose, sucrose, or biomass derived streams.

The second route for BDP production is the catalytic upgrading of succinic acid. With the increase in production of succinic acid in recent years, companies like BioAmber and Myriant are working with partners to find catalysts that can produce BDO from their end products.

Market Overview and Potential Products

BDO has many uses as flexible chemical intermediate to make various polymers, solvents, and other chemicals. Most BDO production goes into tetrahydrofuran (THF) and subsequently PolyTHF, polybutylene terephthalate (PBT), and y-butyrolactone (GBL)[23]. The global BDO market is relatively sizable at 2.5 million MT annually, only 3,000 MT of which is bio-based, and is priced at $2,300 - $2,400/MT[24]. Renewable fibers have been in demand from consumers in recent years and is expected to continue to

[20] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[21] Source: jmprotech.com
[22] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[23] Source: IEA Bioenergy Task 42: Bio-based Chemicals – Value Added Products from Biorefineries
[24] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

rise. Companies like Invista and Nike have incorporated bio-BDO into their spandex products and are helping expand the demand for BDO as a drop-in replacement.

Tetrahydrofuran (THF)
Approximately 45% of the global BDO production is converted into THF, which is used as solvent for many applications and is used in adhesives, cellophane, and PVC cements. It can also be used to produce **PolyTHF** for spandex, polyurethanes resins, or copolyester ethers. The product is sold by Invista as Terathane and PolyTHF by BASF. PolyTHF is formed by acid-catalyzed polymerization of THF[25].

Polybutylene Terephthalate (PBT)
One quarter of total BDO production goes through a reaction with terephthalic acid to produce PBT. PBT is a polymer used as an insulator in the electrical industry, material for plug connectors in the automotive industry and households, swimwear, and synthetic resin used in injection molding. It has properties that make it resistant to solvents, mechanically strong, and heat resistant[26].

y-Butyrolactone (GBL)
Another large market for BDO is for the production of GBL. It is mostly used as a solvent, precursor for solvents, in the production of herbicides, flavoring, and superglue remover.

Commercialization

Genomatica

San Diego company Genomatica develops biobased technologies to enable the production of chemicals from alternative feedstocks for licensing to partners. They have developed processes for 1,4 butanediol called Geno BDO and for bio-based 1,3-butylene glycol among others. In 2013, Genomatica partnered with DuPont Tate & Lyle to demonstrate the technology at their facility with success, they produced 5MM lbs. of bio-BDO in a five-week timeframe. During the same year the technology was licensed by BASF for bio-BDO production and they utilized it into renewable polymers. Genomatica recently announced their technology has reached production of 10,000 tons of BDO worldwide in 2017. A year prior in 2016, the company also announced that the Geno BDO technology would be utilized within the first commercial scale BDO production facility at their partner Novamont's facility in Italy. The $110MM facility has production capacity of 30,000 MT/yr. and is expected to be running at full capacity by the end of 2017[27].

As mentioned previously, another route to the production of bio-BDO is the catalytic upgrading of succinic acid. **Myriant** and **BioAmber** will be profiled in more detail in the succinic acid section of the report but are pursuing routes to produce BDO from their primary product succinic acid.

[25] Source: IEA Bioenergy Task 42: Bio-based Chemicals – Value Added Products from Biorefineries
[26] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[27] Source: www.genomatica.com

Furans

In the furan group, furfural, hydroxymethylfurfural (HMF), and 2,5 furan dicarboxylic acid (FDCA) will be profiled.

Furfural

Furfural was first discovered in 1821 by a German chemist named Johann Wolfgang Dobereiner as a by-product of formic acid production. It remained widely obscure until 1922 when Quaker Oats Company began producing the compound commercially from oat hulls, sugarcane bagasse, and corn cobs[28]. Furfural is a part of the furans class which is classified by any aromatic organic compounds that feature a ring structure composed of four carbon atoms and one oxygen atom. It has a chemical composition of $C_5H_4O_2$.

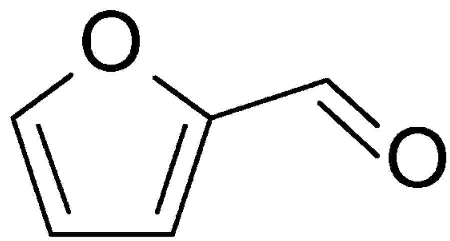

Figure 12: Furfural Chemical Structure $C_5H_4O_2$[29]

Any material that contains pentose sugars (5-carbon) can be used as a feedstock, such as arabinose and xylose, and produces furfural by chemical dehydration. Xylose has been the most widely used starting material which is contained in large quantities in the hemicellulose of lignocellulosic biomass[30]. Furfural is not produced by any petroleum processes so the biomass derived methods do not directly compete with petroleum production as other compounds on the list. However, some of the products that furfural is used to produce may compete with similar petroleum derived products.

<u>Petroleum Production Process</u>

There are no routes for furfural production from petroleum.

<u>Renewable Production Process</u>

Since there is no synthetic route for the production of furfural, it is solely created from biomass by dehydrating pentoses, most often xylose. It can be produced in a one-stage or two-stage process. The one-stage process involves pentosans being hydrolyzed into xylose and then concurrently dehydrated into furfural. The two-stage process uses heat and acid to hydrolyze the pentosans and then the dehydration

[28] Source: furan.com
[29] Source: www.sigmaaldrich.com
[30] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

of xylose to furfural happens in a separate step using acid and steam[31]. The two-stage process receives a higher yield of furfural and is stated to have higher quality.[32]

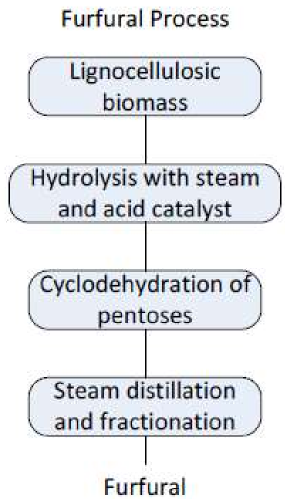

Figure 13: Furfural Production Process[33]

The current commercial processes are primarily produced using corncobs and sugar cane bagasse as the feedstocks. Although production comes from renewable methods, there are issues that production technology must overcome if the furfural market is to grow. The current technology only utilizes the hemicellulose fraction of the biomass and not the lignin or cellulose. These streams are being used to power plants in many commercial operations currently. There is an opportunity to use the streams for higher value products by either matching up with a technology or be used in a biorefinery model to utilize more of the biomass. A NREL paper mentions three other deficiencies with the current technology being: low yields, high energy use, and high sulfuric acid usage. They state that yields with current technology are approximately 50% of hemicellulose which makes up only 17-22% of the total biomass being used. The technologies also have room to improve energy efficiency as it takes 20-50 tons of steam for every ton of furfural produced. Also, sulfuric acid is a large input into the process as it accounts for 20% of total furfural produced. The sulfuric acid is difficult to handle and makes the process harder on equipment[34].

Market Overview and Potential Products

Worldwide furfural production is estimated to be around 270,000 – 300,000 MT annually and 90% of total production is provided by 3 countries: China, Dominican Republic, and South Africa. China is the global leader, producing 70% of furfural production. Furfural prices are estimated to be between $1,000 - $1,450/MT and are heavily dependent on domestic Chinese issues. Since China is the largest producer and consumer of furfural, Chinese droughts, labor issues, government policies, and feedstock cost determine

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[31] Source: Marcotullio: The Chemistry and Technology of Furfural Production in Modern Lignocellulose-Feedstock Biorefineries
[32] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[33] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[34] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

the market prices. It has been reported that corncob prices have been the largest factor for production cost[35].

Furfural has a few applications directly such as a solvent to dissolve aromatics and in the refining of lubricating oils by oil companies. Aromatics and other products are removed from petroleum by a furfural extraction process. However, most of the opportunity lies in using furfural as a platform chemical and is the foundation for many furan-based chemicals.

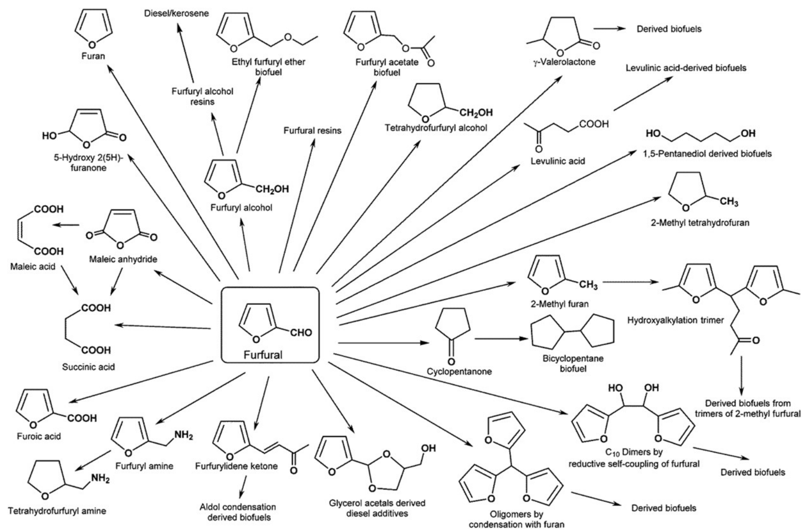

Figure 14: Furfural Derivatives[36]

The chart shows the possible pathways from furfural as a platform chemical, a few of the more prominent chemicals and products will be highlighted.

Furfuryl Alcohol (FA)

FA accounts for 60-70% of total furfural production annually and is used for producing foundry resins. FA has anti-corrosion properties that allow it to be used in reinforced plastics for piping and FA can also be used as a solvent in the coating of DVDs. FA production is a market that is declining in the developed world while growing in developing regions.

Tetrahydrofuran (THF)

THF is created by the hydrogenation of furan, which is produced as a side reaction of the hydrogenation of furfural. THF is a solvent for many applications and is used in adhesives, cellophane, and PVC cements.

2 – Methyltetrahydrofuran (MTHF)

MTHF is a solvent as well and used mostly as a substitute for THF. Compared to THF solvent, it has the potential for higher reaction speeds and better yields, making it an attractive substitute for use in chemical reactions. MTHF is also an alternative fuel component and is used in lithium electrodes.

Tetrahydrofurfuryl Alcohol (THFA)

[35] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

[36] Source: GlucanBio: Furfural PowerPoint

THFA is considered a “green” solvent that has many uses such as in agricultural products, inks, industrial cleaners, and electronics cleaners. It is also a precursor to 1,5-pentanediol which is a plasticizer.

2,5-Furandicarboxylic Acid (FDCA)

FDCA is a substitute for many petroleum chemicals but mostly is a fill-in for terephthalic acid in the production of polyesters. FDCA will be detailed further in its own section below. Furfural to FDCA is a pathway being explored by GlucanBio as FDCA was traditional made from C6 sugars via HMF[37].

Furfural to jet fuel is another pathway that is being explored by the scientific community. It involves a 3-step process where hemicellulose is converted to alkanes with carbons ranging from C7 to C31. This pathway is expected to be a challenge economically due to the lower value of fuel compared to chemicals, although the market is large. The conversion to fuels requires the removal of oxygen which will result in a mass and subsequent yield loss, while chemicals may be able to use the oxygen molecule[38].

Commercialization

As stated previously, a large majority of furfural production takes place outside North America namely in China. Current North American demand is met by imports but there has been a surge in research activity in recent years focusing on furfural as a platform chemical.

In 2011, a company named Lignol Innovations received $30MM in federal funding from the Department of Energy for a demonstration facility to be built at Suncor Energy’s petroleum refinery in Commerce City, Colorado. The biorefinery project would produce furfural, high purity lignin, and ethanol from hardwood biomass. Suncor would be the customer for all ethanol produced on site. Lignol had a change of direction prior to the facility being built and changed the process, feedstock, and product list in order to make the project more commercially viable. The project no longer fell under the criteria for DOE funding and Lignol intended to move forward without the funding[39].

Biofine Technology LLC

Biofine Technology is based in Framingham, MA and was founded by Dr. Stephen Fitzpatrick who developed a levulinic acid technology. More detail will be given about Biofine in the levulinic acid section as it is their primary product but they also produce furfural from the hemicellulose fractions of a variety of biomass feedstocks. The furfural is produced by an acid hydrolysis process and can be upgraded to levulinic acid or sold as product on its own. Biofine has recently updated their pilot plant in Old Town, ME which has the ability to process 250 tons of wood feedstock daily[40].

GlucanBio

GlucanBio was founded in 2012 with technology developed at the University of Wisconsin and Iowa State’s Center for Biorenewable Chemicals. They are pursuing commercialization of the process to produce furan derivatives from biomass, including furfural, HMF, THF, and FDCA. They also have the ability to produce

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[37] Source: IEA Bioenergy Task 42: Bio-based Chemicals – Value Added Products from Biorefineries

[38] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

[39] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

[40] Source: company interviews

dissolving pulp, technical lignin, and nano-cellulose. GlucanBio states that their furfural process which uses an organic solvent has better yields than any existing process. They are currently looking for a strategic partner and are pursuing building a pilot plant[41].

Hydroxymethylfurfural (HMF)

HMF is an organic compound that was first reported in 1875 when it was discovered as an intermediate in the production of levulinic acid from sugar. HMF is naturally occurring in the sugar-containing foods when exposed to heat like cooking or drying. Although furfural has been produced commercially since the 1920's, HMF recently reached commercialization in 2013. It is used as intermediate for levulinic acid and FDCA while having few applications on its own[42]. HMF's chemical composition is $C_6H_60_3$.

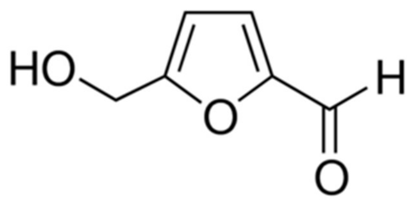

Figure 15: HMF Chemical Structure ($C_6H_60_3$)[43]

Renewable Production Process

HMF is produced by dehydrating C6 sugars such as glucose or fructose. The chemistry is the same as furfural but the starting sugar type is different, furfural is produced from the dehydrating of C5 sugars. HMF is unstable and may undergo conversion to levulinic acid and formic acid, resulting in mixed products and lower yields[44].

Market Overview and Potential Products

The market for HMF is very small as it is an intermediate and does not seem to be sold in the market often. The total market volume has been reported to be 100 tons with a price of over $2600/ton[45]. HMF is the starting point for many bio-based products including many chemicals, converted to monomers for polymers, and use as performance ingredients in food, agriculture, and pharmaceuticals. Although HMF has many possible derivatives and uses, most demand is as an intermediate for FDCA. Many companies have pursued this route to FDCA from C6 sugars via HMF.

Commercialization

[41] Source: glucanbio.com and company interview
[42] Source: IEA Bioenergy Task 42: Bio-based Chemicals – Value Added Products from Biorefineries
[43] Source: www.sigmaaldrich.com
[44] Source: IEA Bioenergy Task 42: Bio-based Chemicals – Value Added Products from Biorefineries
[45] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

HMF's primary use is an intermediate for FDCA and many of the companies that target HMF ultimately produce FDCA and will be profiled in the FDCA section. AVA Biochem produces both HMF and FDCA but HMF is their primary product and will be profiled in this section.

AVA Biochem

AVA Biochem is a specialty chemicals company and the first company to have commercial-scale production for HMF at their Muttenz, Switzerland facility. The company was founded in 2012 and produces HMF along with FDCA and food-grade HMF at their facility. AVA employs a continuous hydrothermal process and does not use fermentation or catalysis. Their plant has capacity to produce 300 MT of HMF at their facility[46].

2,5-Furandicarboxylic Acid (FDCA)

FDCA is a furan derivative that has potential as substitute for multiple petroleum derived chemicals. It was first discovered in 1876 and has been included in the US Department's 12 Top Value Added Chemicals. It has gained attention as a building block primarily because it can substitute for terephthalic acid in the production of polyesters. FDCA has a chemical composition of $C_6H_40_5$.

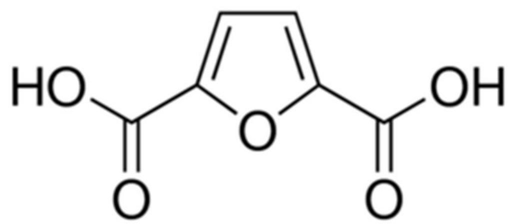

Figure 16: FDCA Chemical Structure ($C_6H_40_5$)[47]

Petroleum Production Process

FDCA does not have a fossil-based pathway or identical substitute.

Renewable Production Process

There are multiple routes to the production of FDCA from renewable methods and they can be categorized in four groups: methods from the dehydration of hexose derivatives, oxidation of 2,5 – disubstituted furans, the catalytic conversion of furan derivatives, and a recent discovery of biological conversion of HMF[48].

Market Overview and Potential Products

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[46] Source: ava-biochem.com
[47] Source: www.sigmaaldrich.com
[48] Source: Weastra: Determination of Market Potential for Selected Platform Chemical

There are very few companies producing FDCA in the market place right now and thus it is not very transparent. It is estimated that there is approximately 45 MT being produced worldwide and the price is not known although it is speculated to be very high. FDCA has not been commercialized to this point because of its high price and limited availability of 5-HMF. Despite this, pilot production has shown validation of pathways and provided information on its potential markets. The potential markets for FDCA are in replacing petroleum based acids in the polymers such as terephthalic acid and adipic acid. There are potential uses in polyesters, polyamides, resins, plasticizers, polyurethanes, and solvents[49].

Replacement of Terephthalic Acid

Terephthalic acid is an important starting material in the plastic market. It is mainly used in polyester production, notably in polyethylene terephthalate (PET), textiles, packaging, consumer goods, coatings, and resins. The structure of FDCA allows it to be a promising functional replacement for terephthalic acid especially with the large market for PET.[50] The substitution of FDCA gives rise to a new polymer called polyethylene furanoate (PEF)[51]. PEF has certain superior properties relative to PET including better barrier properties, tensile strength, higher thermal stability, and lower processing temperature. It can be considered an improvement over PET rather than a replacement and can possibly even be used as a substitute for more expensive aluminum or glass items. Production of PEF from FDCA has environmental advantages over fossil PET with 51-58% reduction in non-renewable energy use. Due to these improvements, PEF has received attention from plastic bottle users Danone and Coca Cola[52].

<u>Commercialization</u>

Synvina

Synvina is a joint venture between Avantium and BASF with headquarters in the Netherlands to produce FDCA and PEF. The venture currently has a pilot facility in Geleen, The Netherlands where they use Avantium's YXY process and fructose as their primary feedstock. The YXY process consists of two catalytic steps: dehydration of the feedstock in an alcohol to produce methoxymethyl furfural and catalytic oxidation of MMF in acetic acid producing FDCA. Currently, Synvina is outsourcing the polymerization of FDCA to PEF to their partners' facilities. The joint venture next steps are to construct a 50,000 MT capacity PEF plant at the BASF location in Antwerp, Belgium and license their technology for commercial scale production. Synvina has also partnered with Mitsui to develop PEF thin films and PEF bottles in Japan, and is developing partnerships with Coca Cola and Danone to explore PEF bottle possibilities[53].

Corbion

Corbion is headquartered in the Netherlands and has over 80 years' experience in fermentation. They consider themselves a global leader in lactic acid and lactic acid derivatives, but they have a Biobased Innovations division that includes a proprietary process they have developed for FDCA. The process is

[49] Source: Weastra: Determination of Market Potential for Selected Platform Chemical
[50] Source: Weastra: Determination of Market Potential for Selected Platform Chemical
[51] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals
[52] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[53] Source: Synvina.com

based on C6 sugars taken to HMF and then FDCA. They are currently producing FDCA in pilot scale and have longer term development plans to get to commercial scale.[54]

AVA Biochem

AVA Biochem, headquartered in Switzerland, is a commercial producer of HMF but announced in 2016 that they added FDCA to their portfolio. Their production will use oxidation to convert HMF to FDCA at their Muttenz, Switzerland plant.[55]

[54] Source: agro-chemistry.com/articles/corbion-takes-steps-process-fdca

[55] Source: ava-biochem.com

Glucaric Acid

Glucaric acid, also called saccharic acid, is an oxidized sugar. It has various uses as a direct product but has received most attention as a starting material for bio-adipic acid. Glucaric acid was named as one of the "Top Value Added Chemicals From Biomass" by the US Department of Energy in 2004. It has a chemical composition of $C_6H_{10}0_8$.

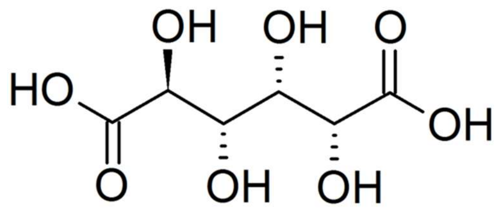

Figure 17: Glucaric Acid Chemical Structure ($C_6H_{10}0_8$)[56]

Petroleum Production Process

There are no pathways to glucaric acid from petroleum.

Renewable Production Process

The primary process to form glucaric acid dates back over a century by oxidizing glucose using nitric acid. The method is utilized for commercial production due to the simplicity of the process using nitric acid as both the solvent and oxidizing agent. Other methods have been reported to use different type of catalysts to oxidize the glucose which can potentially increase yields[57]. Rivertop Renewables utilizes a nitric acid oxidation while Rennovia and Johnson Matthey use a catalyst process.

Market Overview and Potential Products

Glucaric acid is looked at as a promising building block since it is a platform chemical with a wide variety of applications. It can be used in detergents, cleaners, concrete additives, de-icing products, and anti-corrosion markets. The market size is estimated to be 3,000-5,000 MT and the market price is approximately $3,000/MT[58]. The most attention has been paid to glucaric as a phosphate-free detergent builder and as anti-corrosion product to mix in with industrial de-icers. Both Rivertop and Rennovia have pursued both of these direct uses for their product. Glucaric acid can also act as an intermediate for bio-based adipic acid[59].

Renewable Adipic Acid
Adipic acid can be made from glucaric acid by fermentation processes or via hydrodeoxygenation. Adipic acid is used in polyurethanes, resins, and plasticizers. There are other pathways to bio-adipic acid also, it

[56] Source: www.sigmaaldrich.com
[57] Source: Diamond, Murphy, Boussie: Application of High Throughput Experimentation to the Production of Commodity Chemicals from Renewable Feedstocks
[58] Source: company interviews
[59] Source: company interviews

can be made from fatty acids or substituted for by succinic acid in products. Adipic acid is attractive due to its large market size, which was estimated to be 3,000 kilotons in 2015 with over 60% being used in the production of nylons[60].

Commercialization

Rivertop Renewables
Rivertop Renewables, based out of Montana, was the first to the glucaric acid market. They developed a chemical oxidation process that can be flexible with the feedstocks used including various sugars and sugar alcohols. Rivertop primarily target glucaric acid by using nitric acid and oxygen as oxidants and utilizes all carbon atoms of the glucose feedstock. To show the broad applicability of glucaric acid derivatives, Rivertop initially focused on its benefits in detergents and industrial road de-icing solutions.

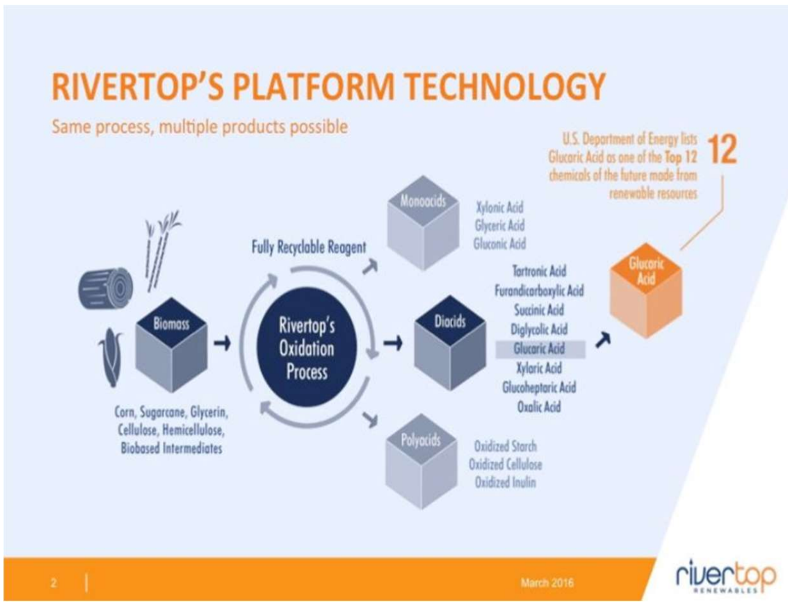

Figure 18: Rivertop's Oxidation Process[61]

In late 2014, Rivertop Renewables started construction on a commercial plant located at DanChem Technologies in Danville, VA. They began producing commercially in August of 2015 with their Riose detergent builder and Waterline and Headwaters corrosion inhibitors. Rivertop has stated that they have exceeded their nameplate capacity during benchmark testing and are capable of producing 9MM dry lbs. of sodium glucarate product annually.

Rivertop raised $26MM in 2014 in a Series B investment round from Cargill, First Green Partners, and their existing investors, but announced their bankruptcy recently. An industry stakeholder states that Rivertop invested resources into pursuing non-phosphate detergents and the product didn't have the market acceptance needed.

[60] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals
[61] Source: www.rivertop.com

Rivertop had secured contracts with the Montana Department of Transportation in past years and Colorado Department of Transportation in 2017 to supply its Headwaters corrosion inhibitor for use on the state roads. The states mix the product with their salt-brine de-icer to prevent corrosion on bridges and vehicles and the biodegradable product will not be harmful to the watersheds[62]. In light of Rivertop's bankruptcy, Rennovia is pursuing the anti-corrosion product and suppling Rivertop's former customers[63].

Rennovia

Rennovia was founded in 2009 and is a specialty chemical company with a focus on processes from renewable feedstocks. They are developing processes to produce glucaric acid, adipic acid, 1,6 hexanediol, and hexamethylenediamine (HMD). Their technologies are based on chemical catalytic process technology and based on models in the petroleum refining and chemical industries. Rennovia announced a collaboration in 2014 with Johnson Matthey to commercialize glucaric acid and adipic acid. In 2017, the collaboration announced a licensing agreement with ADM to provide catalyst and process technology for glucaric acid. The group opened a mini-plant in Stockton, England in 2015 to demonstrate the catalytic aerobic oxidation process of glucose to glucaric acid.

Rennovia has long term goals to develop their hexanediol product but in the short term will develop glucaric acid as an anti-corrosion product. They are working to supply the former customers of Rivertop with product but they state it is a small market currently. Rennovia has set sights on pulp and paper mixed sugar streams as a possible feedstock also and has had talks with pulp mills about that possibility for their anti-corrosion products[64].

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[62] Source: rivertop.com
[63] Source: company interviews
[64] Source: company interviews and rennovia.com

Isoprene

Isoprene is an organic compound that is emitted from plants and trees and is one of the major components that makes up natural rubber. The compound is also an essential building block for synthetic polymers including synthetic rubber. The majority of the isoprene produced around the world is transformed into polyisoprene, which is the synthetic version of natural rubber, to be used in footwear, rubber tires, and sporting goods among other things. Nearly all of isoprene is produced from petroleum derived feedstocks, during a process of extracting the C5 stream from ethylene crackers[65]. Isoprene has a chemical composition of C_5H_8.

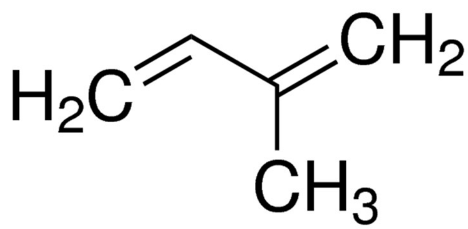

Figure 19: Isoprene Chemical Structure (C_5H_8)[66]

<u>Petroleum Production Process</u>

The industrial production of isoprene results as a by-product of the steam cracking of liquids in the production of ethylene. Naphtha has been the primary feedstock for steam crackers which produces four and five carbon molecules as by-products of value during the process including isoprene. The steam cracking process using naphtha or gas oil recovers the isoprene from the butane/butene stream and then further processes the isoprene concentrate through extractive distillation[67].

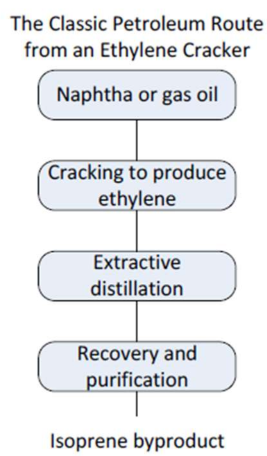

Figure 20: Isoprene Petroleum Process[68]

[65] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[66] Source: www.sigmaaldrich.com
[67] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[68] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

The steam cracking process is the primary source of isoprene production in the US but the shift towards more shale gas production has the ability to change the outlook for isoprene going forward. With shale gas production, lighter feedstocks like ethane, propane, and butane can be used for ethylene production from a steam cracker. These feedstocks increase the ethylene yield but produces no four or five carbon by-products during the process. If steam crackers continue to shift towards lighter feedstocks, traditional production of isoprene will decrease and open an opportunity for biobased methods to fill the gap.

Renewable Production Process

Renewable processes use aerobic biological conversion to convert sugar streams to renewable isoprene. After the conversion takes place, the isoprene is recovered in the gas phase and allows for simple purification to match product specifications.

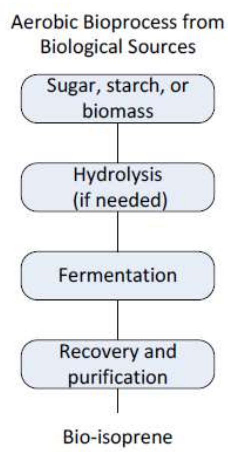

Figure 21: Isoprene Renewable Process

The collaboration between Amyris and Michelin produced bio-isoprene using a genetically modified yeast for their biological conversion of glucose. The Goodyear and DuPont partnership technology used an engineered E. coli to convert the biomass feedstock[69].

Market Overview and Potential Products

The total market volume for isoprene is estimated to be 850,000 MT and nearly all is petroleum based. Approximately 60% of the volume is used in producing polyisoprene rubber, styrene polymers, and butyl rubber for tire manufacturing. An estimated 30% is used for adhesives while medical and personal care products account for the remainder. The isoprene market is heavily reliant on tire manufacturing and follows trends in transportation. Isoprene is estimated to cost $2000/MT although long-term pricing arrangements are common in the industry and data is scarce[70].

There are two main market drivers for the growth of renewable isoprene in the market. If the petroleum industry shifts to lighter feedstocks for ethylene cracking, fossil-derived isoprene supply will decrease.

[69] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[70] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

This has the ability to drive demand for bio-isoprene. The second driver is the interest in having a renewable product for environmental benefit and corporate image. The renewable product would still have to compete on price and quality to build demand in the market regardless.

<u>Commercialization</u>

Goodyear/DuPont

Commercialization of renewable isoprene technologies has been slow to develop but there has been significant interest from major tire producers. The first announced research collaboration for bio-based isoprene was between Goodyear and DuPont Industrial Biosciences in 2008. They trademarked the term BioIsoprene for their product and have produced prototype tires in recent years. The technology uses an engineered E. coli that produces isoprene from biomass[71]. They planned to invest in a pilot facility in 2016 but there has been no recent press releases on the matter.

Amyris/Michelin/Braskem

Amyris and Michelin announced a collaboration in 2011 to develop and commercialize renewable isoprene to use in rubber products including tires. Amyris's technology was originally used to produce a 15 carbon molecule called farnesene but can also convert sugars into isoprene which is a 5 carbon molecule. The initial announcement stated that initial commercial production would begin as early as 2015. In 2014, Brazilian petrochemical company Braskem joined the collaboration to accelerate the commercialization as a global leader in biopolymers[72].

[71] Source: biosciences.dupont.com/global-challenges/protection/

[72] Source: amyris.com press release

Itaconic Acid

Itaconic acid is a naturally occurring acid with 5 carbon atoms that was included in the Department of Energy's Top 12 Value Added Chemicals. The non-toxic and biodegradable powder was initially obtained by the distillation of citric acid but it has been produced industrially by fermentation of carbohydrates since the 1960's[73]. Itaconic acid has a chemical composition of $C_5H_60_4$.

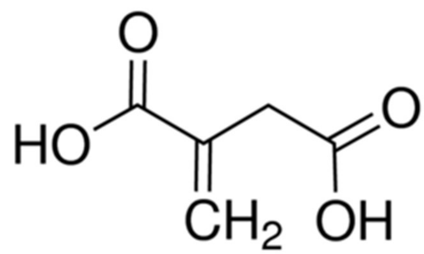

Figure 22: Itaconic Acid Chemical Structure ($C_5H_60_4$)[74]

Petroleum Production Process

There have been references to itaconic acid being produced by the oxidation of isoprene or using maleic anhydride as starting material but no detailed accounts of the processes. Itaconic acid is almost entirely produced by fermentation of sugars and other processes do not compare favorably.

Renewable Production Process

Itaconic acid was historically produced by chemical methods, the main method being the distillation of citric acid prior to 1960. Today, itaconic acid is produced industrially by the fermentation of carbohydrates such as glucose and sucrose using fungi and carries a high cost of production with current methods. The most widely used fungus is A. terreus but A. itaconicus can be used as well. Itaconic acid production has mostly used first generation feedstocks to this point but second generation feedstocks are being explored to lessen the competition with food products. The challenge for non-food feedstock has been the variability in composition and the presence of impurities from pretreatment processes have lowered yields considerably[75].

Market Overview and Potential Products

Itaconic acid has received attention as an important chemical intermediate but only has applications in niche markets to this point. The current use for itaconic acid and derivatives are in lubricant additives, surface agents, dyes, plastics, synthetic rubber, resins, and fibers. The market size was estimated at 41,000 MT in 2015 and nearly all production comes from China. As the main player, China controls both the

[73] Source: Weastra: Determination of Market Potential for Selected Platform Chemical
[74] Source: www.sigmaaldrich.com
[75] Source: Weastra: Determination of Market Potential for Selected Platform Chemical

majority of supply and demand for itaconic acid today. The market price for the chemical is between $1,800 - $2,000 per MT[76] depending on the grade and quality of the itaconic acid provided.

The production methods for itaconic acid are costly for certain applications and has thus limited the market to specialized applications where the price can be accepted. The main use of itaconic acid currently is in the production of styrene-butadiene rubber and synthetic latexes used in the paper and architecture coating industry. It is also used in paints for improved quality and in chelant dispersant agents. Other derivatives have found use in medicine, cosmetics, and herbicides. The growth market potential for itaconic acid moving forward is expected to be from polyester resins, absorbent polymers, phosphate free detergents, and use in methyl methacrylate[77]. A few applications in the addressable market will be highlighted below.

Polymethyl Methacrylate (PMMA)

PMMA is a strong, transparent material that is a lightweight, shatterproof alternative to glass that is used in construction. It has been marketed by names such as Plexiglas or Acrylite. Acetone cyanohydrin is currently the starting material for methyl methacrylate (MMA) and itaconic acid has the potential to substitute for this chemical in production of MMA. In order to be successful in in replacing acetone cyanohydrin, itaconic acid will have to be cost competitive or bio-based PMMA will not be successful in achieving growth demand for itaconic acid. Commercial production of bio-based PMMA is expected in coming years[78].

Superabsorbent Polymers (SAP)

SAP's are used in diapers, feminine hygiene products, and similar applications. Currently, SAP's are made from polymerized acrylic acid. This market has potential for itaconic acid since itaconic acid can be polymerized to create polyitaconic acid which has similar properties and has potential to replace petroleum derived polyacrylic acid.

Unsaturated Polyester Resins (UPR)

UPR are the most popular type of resins used in composites for production of fiber reinforced plastics in the marine or automotive industries. They have also been used in production of the blades on wind turbines. The starting material used in most UPR production is maleic anhydride and itaconic acid has an opportunity to replace this chemical as it has a similar structure. Itaconic acid would not be a drop-in replacement but a comparable substitute. The UPR market is expected to see growth due to greater use in automotive parts to replace metal parts to achieve lower weight. However, itaconic acid will have competition from other bio-based building blocks to replace maleic anhydride like fumaric acid. Estimates have shown that itaconic acid may replace up to 5% of maleic anhydride in UPR by year 2020.

Detergent Builders

Detergent builders help support surfactants in the washing process to increase and protect the cleaning efficiency. The most common detergent builder has been sodium tripolyphosphate (STPP) but is being

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[76] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

[77] Source: Weastra: Determination of Market Potential for Selected Platform Chemical

[78] Source: Weastra: Determination of Market Potential for Selected Platform Chemical

outlawed in North American and Europe for eutrophication risk from phosphates. Itaconic acid has the potential to replace STPP in a portion of detergent builders and growth is expected in overall itaconic use as chelating agents.

Commercialization

The majority of production comes from China today. The US had Cargill as a market leader in the past but once they left the market, production shifted to China. The market dynamics are not very transparent but the two companies mentioned seem to be producing itaconic acid today.

Qingdao Kehai Biochemistry
Qingdao Kehai Biochemistry is thought to be the global leader with production of 10,000 MT annually. The company also produces sodium gluconate with capacity of 50,000 MT. They are located in south Shanghai and were established in 2003. The company has a bio-fermentation engineering research facility where they are looking at other derivatives for development[79].

Itaconix
Itaconix PLC is based in Flintshire, UK and has an American office in Stratham, NH. They are listed on the London Stock Exchange and state they are the world leader in polymers from itaconic acid. Itaconix products include non-phosphate detergent builders, personal care polymers, binders for paints and coatings. The company announced in 2017 that it had signed a partnership with specialty chemical company AkzoNobel to develop bio-based chelates for use in detergents and cleaners[80].

[79] Source: Weastra: Determination of Market Potential for Selected Platform Chemical
[80] Source: Itaconix.com

Lactic Acid

Lactic acid is a carboxylic acid and is widely seen in nature. It was first discovered in 1780 by a Swedish chemist named Carl Wilhelm Scheele after being isolated by sour milk. It has been produced commercially as early as 1880 when Charley Avery set up a fermentation plant in Littleton, MA[81]. Lactic acid has many uses in food products especially and is a precursor to polylactic acid, a polyester. It has a chemical composition of $C_3H_60_3$.

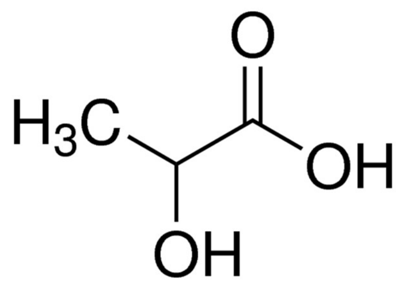

Figure 23: Lactic Acid Chemical Structure ($C_3H_60_3$)[82]

Petroleum Production Process

The large majority of lactic acid if produced via microbial fermentation of carbohydrates but there is a chemical synthesis process that uses acetaldehyde as the starting point.

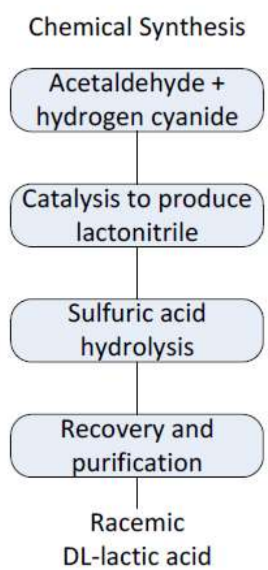

Figure 24: Lactic Acid Petroleum Process[83]

[81] Source: Wikipedia.org
[82] Source: www.sigmaaldrich.com
[83] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

A company from Japan called Musashino Chemical Laboratory produces 7k metric tons annually or 2% of total global production via the synthesis process. The process uses acetaldehyde and hydrogen cyanide to form lactonitrile. The acetaldehyde is produced by the oxidizing of ethylene or hydration of acetylene[84].

Renewable Production Process

The majority of the global lactic acid production is formed by anaerobic bacterial fermentation. Companies like Cellulac, Purac, and Natureworks are pursuing processes that use lignocellulosic biomass to produce the lactic acid[85].

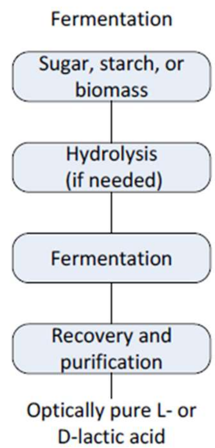

Figure 25: Lactic Acid Fermentation Process[86]

Market Overview and Potential Products

Lactic acid has many uses commercially including in food products. It can be used as an acidulant, flavoring agent, curing agent, and food preservative. The odorless and non-volatile compound is approved for use as a food additive in the US, EU, Australia, and New Zealand. Along with food, Lactic Acid also has uses in pharmaceuticals, cosmetics, and detergents due to its biocompatibility. However, the main driver of growth in future consumption of lactic acid is predicted to come from its ability to be a precursor to polymers. The global market for lactic acid is approximately 472,000 MT and is priced around $1,500/MT[87].

Polylactic Acid (PLA)

PLA is a biodegradable transparent bioplastic that has uses in the medical implants, textiles, and packaging material. It is created by using both molecules, D-lactic acid and L-lactic acid, along with catalysts. The medical community has interest in using PLA as a material for implants due to its ability to degrade down to lactic acid within 6 months to 2 years within the body. It can be used for screws, bolts, plates, pins,

[84] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[85] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[86] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[87] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

rods, and mesh since it will gradually degrade to shift the load to the body naturally over that time frame. The textile market also is an interesting fit for PLA since it can create smooth fabrics with UV resistance, low flammability, and moisture resistance. The largest market opportunity which will be drive demand for lactic acid in future years will be its use as a decomposable material for packaging and other uses. It has been used for cups, bags, food packaging, disposable tableware, feminine hygiene products, and diapers. With increasing consumer awareness for sustainability, recyclability, and green products, PLA is expected to be in high demand to replace petroleum plastics in the future[88].

Large retailers like Target and Walmart have indicated in past years that PLA use could help them meet sustainability goals, while Stonyfield Farm actually made the switch in 2010 for their packaging. Many have indicated the PLA could be an option for their packaging but information about companies using the product today is harder to come by[89].

Commercialization

Cellulac

Cellulac, based out of the UK, developed a chemical and process engineering technology to form lactic acid from 2nd generation feedstocks including lignocellulosic material and lactose whey. They have the ability to use wheat straw, distilled dried grains with solubles, and spent brewer's grains for lignocellulosic feedstocks. Cellulac announced in 2015 that they would purchase the Great Northern Brewery in Dundalk, Ireland to reconfigure to produce lactic acid for use in PLA. The plant would produce 20,000 MT of lactic acid in the first phase and increase to 100,000 MT in an expansion. They plan on deploying the technology in ethanol plants or dairy providers through joint ventures or licensing agreements in the future. Cellulac states that their production costs of pure D-lactic acid are 40% below other current commercial producers[90].

Natureworks

Natureworks began in 1989 as a Cargill research project to look for uses for carbohydrates from plant based feedstocks for sustainable plastics. This eventually became a joint venture between PTT Global Chemical and Cargill. The Natureworks technology uses plants like corn, sugarcane, cassava, and sugar beets and puts them through a milling process to extract glucose. Enzymes are added to convert the glucose to dextrose by hydrolysis and then microorganisms ferment the dextrose into lactic acid. Natureworks then applies a proprietary process to convert the lactic acid to rings of lactide which is then polymerized to PLA, which Natureworks refers to as Ingeo. They state that their customers use the Ingeo polymers and fibers to make a range of products from yogurt cups to baby wipes.

Natureworks has a manufacturing plant in Blair, Nebraska that came online in 2002 and has a capacity of 150,000 MT of Ingeo PLA. Alongside that production facility, they built the world's largest lactic acid production plant in 2003 to feed the polymer facility next door. Natureworks has also recently opened a fermentation laboratory to research and develop methane to lactic acid technology[91].

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[88] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals
[89] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[90] Source: cellulac.com/sf/
[91] Source: natureworksllc.com

Corbion

Corbion is headquartered in the Netherlands and has over 80 years' experience in fermentation. As a global leader in lactic acid and lactic acid derivatives, they generated sales of 911M Euro in 2016 and employ over 1600 people. Corbion has two separate lines of business: Biobased Ingredients and Biobased Innovations. Biobased Ingredients is their core business that focuses on lactic acid based ingredients for food and biochemicals. Biobased Innovations contains their new biotechnology platforms including a joint venture with Total for production and marketing of PLA and joint venture with BASF dealing with succinic acid called Succinity. The company also plans for longer term development plans for FDCA and lignocellulosic feedstocks for lactic acid production. Corbion has lactic acid production facilities in Thailand, United States, Brazil, The Netherlands, and Spain[92].

[92] Source: corbion.com and company interviews

Levulinic Acid (LA)

Levulinic acid was mentioned for the first time in 1840 by a Dutch professor and was produced commercially for the first time 100 years later[93]. It gained more notoriety recently when it was named as one of the "Top Value Added Chemicals From Biomass" by the US Department of Energy in 2004. Levulinic acid has a chemical composition of $C_5H_8O_3$.

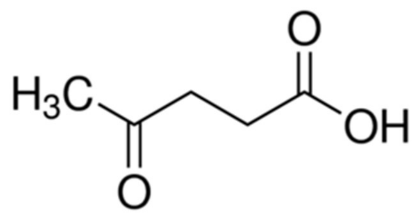

Figure 26: Levulinic Acid Chemical Structure ($C_5H_8O_3$)[94]

Petroleum Production Process

There are no petroleum derived production processes for levulinic acid.

Renewable Production Process

Levulinic acid is produced from renewable feedstocks by acid hydrolysis of starch or the C6 sugars in lignocellulosic biomass. Five carbon sugars as in hemicellulose can produce LA as well by using an acid treatment followed by a reduction step. Many of the commercial processes for LA are based on this same strong acid technology. When the acid hydrolysis of the lignocellulose takes place the polymer sugars break down to C5 and C6 sugars. The C6 sugars are degraded to HMF which can be converted to levulinic acid via hydration and formic acid. The C5 sugars result in furfural production which can be used as a product or upgraded to LA also. The leftover product is a char mixture of lignin and degraded cellulose and hemicellulose[95].

[93] Source: Wikipedia.org
[94] Source: www.sigmaaldrich.com
[95] Source: Tecnon OrbiChem: Handbook of Commercial Bio-Based Chemicals (Prospectus)

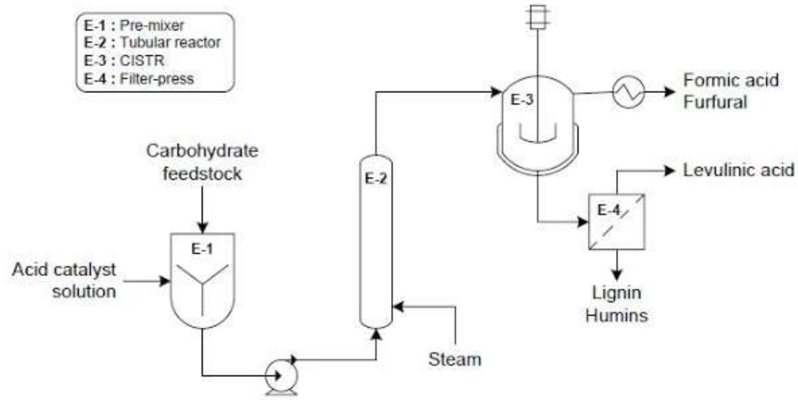

Figure 27: Biofine Process[96]

This process has been has gained attention for industrial production as it has less intractable by-products which can be challenging to remove. Yields can vary based on the acid type, its concentration, temperature, and pressure used in the process. In the 1990's the first process to be used near commercial scale was the Biofine Process, established by Dr. Stephen Fitzpatrick and now being further developed for commercial use by Biofine Technology, LLC[97].

<u>Market Overview and Potential Products</u>

Levulinic acid has a very small market for direct use and total market size is estimated to be 7,000 MT globally. The niche market has high prices with LA selling for $5,000/MT on the low end up to $8,000/MT. Commercial production of LA is contained to a few small producers in China currently, these companies also produce furfural. LA has a small market for direct use and its applications are mostly in cosmetics, food preservation, and pharmaceuticals. Levulinate salts are used as a preservative and conditioning agent in products like anti-aging creams or as a preservative for meats and other foods. Calcium levulinate can be used as a calcium supplement or nutritional enhancement in pharmaceutical products. With very small markets for direct use, many technology companies are focusing efforts on LA as a platform chemical and are exploring its potential derivatives[98].

Levulinic acid has the ability to be the platform for a range of derivatives with potential to access various high volume chemical markets. A few promising compounds and applications that are being developed will be highlighted.

Ethyl Levulinate (EL)

Ethyl levulinate is a levulinic acid ester and it can be made by esterification of levulinic acid with alcohols. The main esters: methyl-, ethyl-, butyl levulinate all have numerous potential and current uses including fruity flavor and fragrance ingredients but we will focus on ethyl levulinate as its been shown recent attention by producers, especially Biofine. EL is currently made from furfural which is an expensive process

[96] Source: De Jong: Overview of Biorefineries based on Co-Production of Furfural
[97] Source: Tecnon OrbiChem: Handbook of Commercial Bio-Based Chemicals (Prospectus)
[98] Source: Tecnon OrbiChem: Handbook of Commercial Bio-Based Chemicals (Prospectus)

and production from LA has the potential to be more cost competitive. It has existing markets as a biodiesel modifier, in perfume, cosmetics, cigarettes, and solvents (Bio PP). Many producers are looking towards EL as a safer alternative in the solvent market and also for its properties as a fuel. Levulinate esters have greater miscibility with petro-fuels than soy diesel or ethanol and thus mixtures can be pipelined instead of blended at the pump[99]. Biofine is primarily looking at EL for its potential as heating oil additive and are currently testing with the National Oilheat Research Alliance (NORA) and a large heating oil company. The largest advantage for heating oil as an addressable market is the potential to receive a cellulosic RIN which would be a tremendous boost to the economics. The heating oil market is over a 3 billion gallon market and Biofine is working on 10% LA blends currently[100].

Levulinic Ketals

Levulinic ketals are formed by combining esters of levulinic acid with alcohols and were developed by Segetis. They have a wide range of applications including biodegradable solvents, phthalate-free plasticizers, and polyols. The solvents and plasticizers are already being sold on the market on a small-scale.

y-Valerolactone (GVL)

GVL can be produced by hydrogenation and dehydrating LA with help from a metal catalyst. It can be used as a perfume or food additive with its fruity aroma, solvent for lacquers, insecticides, and adhesives. GVL has benefits as a solvent due to high power and low vapor pressure. It can also be used as an intermediate to form 2-methyl tetrahydrofuran (MTHF) through its reduction. MTHF is a fuel component and is attractive as a solvent. Compared to THF solvent, it has the potential for higher reaction speeds and better yields, making it an attractive substitute for use in chemical reactions.

Diphenolic Acid (DPA)

DPA is garnering interest as a substitute for bisphenol A (BPA), a component of polymers. BPA has received negative attention as a potential health risk when used in plastics for food packaging and bottles. DPA can find a market in BPA-free polymers[101].

Commercialization

Biofine Technology LLC

Biofine was started in 1987 to control the patents to the levulinic acid technology and license agreements for certain derivatives. The Framingham, MA company was founded by Dr. Stephen Fitzpatrick and was awarded a grant by the DOE to construct a demonstration plant in Glens Falls, NY in 1994. The plant operated at that location for 10 years and then the company constructed a pilot facility in Old Town, ME for development going forward. In 1999, Biofine received the Presidential Green Chemistry Award in 1999 for their LA technology and have invested $35M into the company and technology to this point.

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[99] Source: Grandview Research: Ethyl Levulinate Market Analysis by Application (Flavors, Fragrances), Potential Downstream Applications and Segment Forecasts To 2022

[100] Source: company interview

[101] Source: Source: Tecnon OrbiChem: Handbook of Commercial Bio-Based Chemicals (Prospectus)

Their process is stated to have the ability to process nearly any ligno-cellulosic material such as paper mill sludge, paper and wood wastes, and agricultural residues. Biofine has a preference for wood or pulp but can use any biomass with cellulose content above 30%. The process creates coproducts of furfural, formic acid, and ligneous char; the coproducts have value as products on their own while the two former products have more high value uses. The Biofine process is a quick process, taking less than 30 minutes which they state is faster than any competitors. The company also holds patents to produce 3-HPA and succinic acid and will explore opportunities in those areas.

Biofine announced that the pilot plant in Old Town, ME has been newly updated and occupies a 100,000 square foot space. They have the ability to process 250 tons of wood daily and they will be exploring the use of levulinic acid as jet fuel in the space with the University of Maine. Biofine is targeting the potential for ethyl levulinate as a heating oil additive and believe this could be a large opportunity with access to cellulosic RINs moving forward. The company is currently testing this product with NORA and a large heating oil company[102].

GFBiochemicals

GFBiochemicals was founded in 2008 by Pasquale Granata and Mathieu Flamini, a long time professional soccer player in Europe. The company, headquartered in Milan, states they are the only company to produce levulinic acid at commercial scale from biomass. Their platform technology called Atlas Technology allows feedstock flexibility such as wood, wheat straw, grass, and other cellulosic wastes. The continuous process technology also recovers and purifies the levulinic acid while separating out char for energy and producing formic acid.

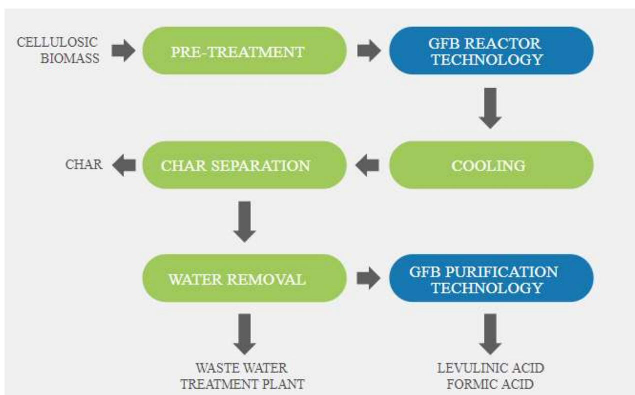

Figure 28: GF Biochemicals Atlas Technology[103]

GFBiochemicals has their proprietary technology on display at commercial scale at their plant in Caserta, Italy which announced start up in 2015 with a capacity of 1,200 MT of levulinic acid. The production began by using corn starch feedstock but GF Biochemicals had planned on switching to wood waste feedstock in 2016; it is unclear if that change took place. The company announced plans to increase capacity to 10,000 MT in 2017 at Caserta. We have heard around the industry that the Caserta plant may not be producing levulinic acid at this point but we have not been able to verify one way or another.

GFBiochemicals has shown interest in expanding into downstream applications in recent years. In 2016, they acquired Segetis, a US-based levulinic acid derivatives producer with over 50 patents and 200

[102] Source: biofinetechnology.com and company interviews
[103] Source: GFbiochemicals.com

pending patent applications. The acquisition allows GF Biochemicals to match their commercial-scale technology with technology to convert that into many biobased intermediates and chemical. The acquisition includes the Segetis pilot plant in Minnesota and their Javelin technology for levulinic ketals. The company announced a joint development with American Process Inc. in 2017 to develop a large bio-refinery in the US. The joint development will look to repurpose an old industrial site and each company plans to manufacture products at the site. GF Biochemicals plans to manufacture bio-polyols, bio-plasticizers, bio-esters, and bio-solvents while API will produce bioethanol, nanocellulose, and cellulosic sugars[104].

GF Biochemicals has had multiple announcements in recent years yet it is unclear if they are producing product currently out of their Caserta plant. Industry stakeholders believe that the production facility is currently idle[105].

Bio-on S.p.A. and Sadam S.p.A.

Bio-On, an Italian bioplastic intellectual property company, and Sadam, a food and agro-industrial company, have announced a project to develop processes for the commercialization of levulinic acid. The plans include a pilot plant for research and a demonstration plant with capacity of 5,000 MT of levulinic acid production at Sadam's San Quirico plant in the province of Parma, Italy[106].

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[104] Source:gfbiochemicals.com
[105] Source: company interview
[106] Source: Biofuels Digest: Bio-on and Sadam team up to develop competitive, sustainable levulinic acid from beet waste

Para-xylene (pX)

Para-xylene, an aromatic hydrocarbon, has attracted attention by purchasers of PET bottles like Coca Cola and Pepsi since it can be used to produce renewable PET. The chemical has numerous pathways from petroleum and renewable feedstocks and is primarily used in the production of terephthalic acid. Para-xylene has a chemical composition of C_8H_{10}.

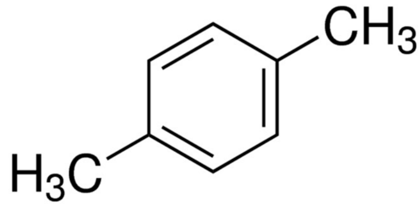

Figure 29: P-Xylene Chemical Structure[107]

Petroleum Production Processes

There are many routes to produce para-xylene from petroleum. One method is a side stream of aromatics that results from the petroleum refining process at a conventional refinery operation. The aromatic stream includes benzene, toluene, and xylene and the p-xylene is separated out in processes of distillation, crystallization, and reaction. These separation steps are the major cost factors in the production of para-xylene. Another route for production comes from the cracking of naphtha and gas oil feedstocks which produces streams containing xylene among aromatics.

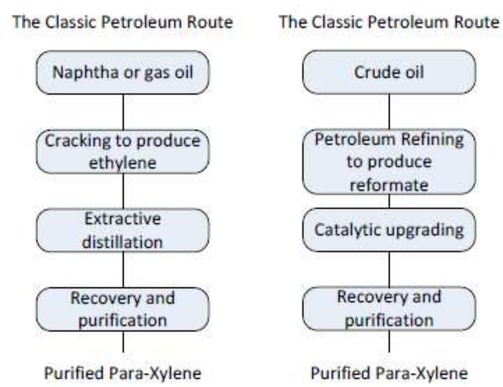

Figure 30: Para-xylene Petroleum Process[108]

Renewable Production Processes

There are various methods to produce Para-xylene from renewable sources that are being pursued in the marketplace. These processes range from thermochemical pyrolysis to biochemical fermentation with upgrading to pX and hybrid technologies that involve catalytic upgrading. The different technologies have the ability to process either all of the biomass or certain streams and also range in the end product produced. The technologies either produce pure pX or BTX (benzene, toluene, xylene) comparable fossil

[107] Source: www.sigmaaldrich.com
[108] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

reformate to be upgraded to pX. The differing technologies for 5 main pX players will be described in more detail[109].

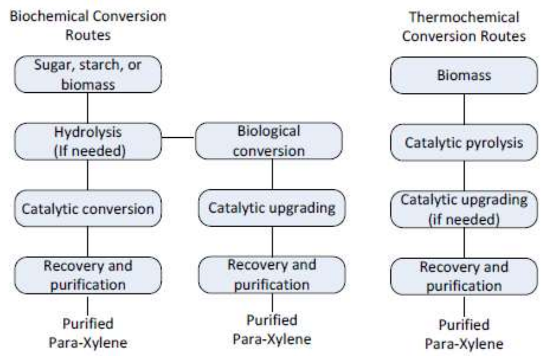

Figure 31: Para-xylene Renewable Production Process

Gevo has developed a process that converts isobutanol to pX. A biomass sugar stream is fermented to the isobutanol by a yeast that has the ability to convert C5 and C6 sugars. The isobutanol is then dehydrated to isobutylene by a catalyst such as sulfuric acid, then dimerized to diisobutylene by an oligomerization catalyst. The diisobutylene undergoes dehydrocyclization to produce pX and hydrogen from an alumina- or silica-based catalyst in the final step.

Origin Materials, formerly Micromidas, is in the process of developing a method for bio-pX by a chemical catalytic process from cellulosic biomass. The company states that it uses a 3-step chemical process utilizing reactors that can handle various waste feedstocks. Para-xylene is produced from either 2,5-hexanedione directly or 2,5-dimethylfuran to hexanedione via hydration. The hexanedione is reacted with ethylene by catalysts and solvents producing the pX.

Virent is also in the renewable pX space and they have a process involving a hybrid biochemical and thermochemical process called their BioForming process. The biomass is converted to an aromatic stream called BioFormate, similar to fossil reformate. This product can be upgraded to renewable aromatics including pX with the same processes used in petroleum production.

Annellotech has pursued a thermochemical process for pX production called the Bio-TCat Process. They use a catalytic fast pyrolysis that originated from Prof. George Huber at University of Massachusetts. Annellotech can use a broad range of feedstocks to create a renewable BTX (benzene, toluene, xylene) that can be upgraded to aromatics including pX.

Another company called Biochemtex has developed a technology that produces BTX but they can use lignin feedstocks. Their MOGHI process uses lignin from their subsidiary, Beta Renewables' cellulosic ethanol process and converts to BTX in the presence of hydrogen, a nickel catalyst, and a solvent[110].

Market Overview and Potential Products

[109] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[110] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

Para-xylene is a large global market with volume above 35 million metric tons. China, India, and Korea account for more than 70% of global pX production and Asia is also the largest consumer. The United States is the fourth largest pX producing country with BP being its highest producer and consumer[111].

Prices for pX have stayed more reasonable than other chemicals in the renewable space as the market is so large. Platts Para-xylene Index shows that prices have generally stayed between $750/MT and $900/MT over the last year and a half. The market current sits just above $800/MT for pX[112].

Figure 32: Platts Global Xylene Index Prices[113]

Para-xylene is used in the production of terephthalic acid and dimethyl terephthalate (DMT), the two raw materials for PET fiber and bottles. It is estimated 97% of pX is used to produce polyesters, 65% of which is for fibers, 27% for PET resin, and the remaining amount is for film and other uses.

Coca-Cola, Nike, Procter & Gamble, Heinz, and Ford announced a collaborative effort in 2012 to promote the research and development of 100% renewable material derived PET. They found that the technological and economical challenges associated with the production of pX is the purification needed to achieve adequate quality for commercial applications. Commercial pX has a purity specification of 99.7% from petroleum, especially for plastic bottles. The biomass-derived technologies at the time had varying impurities that put renewable pX at a disadvantage to fossil based methods.

The main driver for the renewable pX market will be the production of purified terephthalic acid. Renewable processes will have to meet the specifications and economics of current petroleum products in order to compete[114].

<u>Commercialization</u>

Anellotech

Anellotech, based in Pearl River, NY, has developed a thermal catalytic process described previously to produce bio-aromatics that are identical to petroleum aromatics. The "drop-in" BTX stream produces

[111] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

[112] Source: Platts

[113] Source: Platts

[114] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

polyesters, polystyrenes, polycarbonates, nylon, and polyurethanes from these streams. Anellotech has secured long term partnerships with Johnson Matthey, IFP Energies nouvelles, Axens, Suntory, and Toyota Tsusho Corporation for process development, catalysis, engineering design, and licensing. The company announced in early 2016 the construction of development and testing facility in Silsbee, TX to showcase the technology[115].

Biochemtex

The Italian company Biochemtex is the majority shareholder in Beta Renewables and developed the PROESA technology utilized for their second generation ethanol production. Another technology that they are developing is called MOGHI which converts lignin to bio-naphtha and BTX. Biochemtex is pursuing a project to build a biorefinery next to the Beta Renewables ethanol facility to offtake the lignin for processing.

Gevo

Englewood, CO based Gevo has a strategy to displace petroleum based products with identical chemicals from renewable material. Their focus is on isobutanol to produce fuels, chemicals, plastics, and fibers. They have acquired a facility in 2010 in Luverne, MN that they converted to their first isobutanol plant. The facility has the ability to produce both isobutanol and ethanol concurrently and stated they planned on producing 750,000 gallons of isobutanol and 15 million gallons of ethanol in 2016. There is no indication that they met their targets. Gevo also operates a biorefinery in Silsbee, TX that converts isobutanol from their Luverne plant into hydrocarbon products like jet fuel, octane, and ingredients for polyester. The plant was updated in 2013 to produce para-xylene as well in sponsored pilot development by Coca Cola[116].

Origin Materials

Sacramento renewable materials start-up Origin Materials changed its name from Micromidas in early 2017. Around the same time the company announced the closing a second round of venture capital that raised $40MM and brought on Nestle and Danone as investors and partners. Origin is developing a process to produce bio-pX and ultimately bio-PET from biomass using a catalytic process. The company has a pilot plant in Sacramento and plans to have a commercial scale demonstration facility in Sarnia, Ontario by the end of 2018. Bioindustrial Innovation Canada made an investment in Origin through their Sustainable Chemistry Alliance Investment Fund to have the facility built in their biorefinery cluster in Sarnia. Origin states their goal is to produce 5,000 MT of PET bottles in their first year of production. The company has raised over $80MM in venture financing since they were founded in 2008[117].

Virent

Virent was founded in 2002 in Madison, WI by Randy Cortright. Over the last 15 years, Virent's strategy has been to commercialize their BioForming technology to produce renewable fuels and chemicals. In 2010, Virent and Shell partnered to produce biogasoline at the world's first biogasoline demonstration plant in Madison, capable of producing 10,000 gallons annually. Soon afterwards, Virent closed funding from Royal Dutch Shell and Cargill while starting to produce biodiesel. Virent began to produce pX from

[115] Source: anellotech.com
[116] Source: gevo.com
[117] Source: originmaterials.com

plant sugars added Coca Cola to the list of top partner companies. Last year, Virent established a consortium for the commercialization of their technology that consists of Tesoro, Johnson Matthey, Coca Cola, Shell, and Toray. Tesoro acquired the majority share of Virent soon afterwards. With powerful partners and investors behind Virent, announcements for commercial plants seem likely but have not been seen yet[118].

[118] Source: virent.com

1,3 – Propanediol (PDO)

PDO was first identified as a chemical produced by biological production in 1881. It has been produced by petroleum processes in the past but faded as the bio-based product came onto the market[119]. PDO is a clear case where the bio-based product has an apparent advantage over the petroleum process. It can be found in consumer and household products, as well as a precursor to polyesters. PDO has a chemical composition of $C_3H_80_2$.

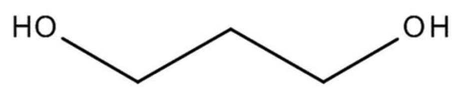

Figure 33: PDO Chemical Structure ($C_3H_80_2$)[120]

Petroleum Production Process

1,3 propanediol (PDO) has only recently been synthetically produced from petroleum and production did not last long before giving way to biobased methods. The Shell Chemical Company began commercial production of PDO in 1998 after researching its production since 1960. In their commercial process, Shell used a cobalt catalyst for the hydroformylation of syngas and ethylene oxide to create HPA. The HPA is subsequently purified and hydrogenated to PDO which is then purified by a distillation process.

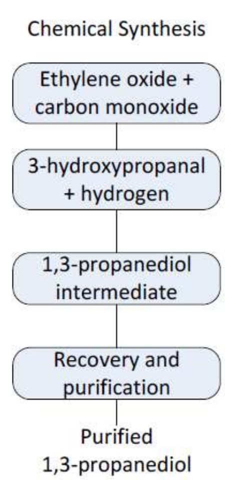

Figure 34: PDO Chemical Synthesis[121]

[119] Source: Wikipedia.org
[120] Source: www.sigmaaldrich.com
[121] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

Shell used the PDO as feedstock to produce PTT under their product name Corterra. Shell produced the PTT at a Louisiana plant that reached 83,000 tons at its highest point but closed in 2009 as it was not a profitable business for them[122].

Renewable Production Process

There are two routes for the renewable production of PDO, it can be made using glucose or glycerol as the starting material. The method from glycerol was first discovered in 1881 where it was discovered that PDO production from glycerol fermentation was found in many microorganisms. However, in 2004 Dupont Tate and Lyle announced that they would using an aerobic bioconversion process to produce PDO from the glucose from wet milled corn starch. DuPont and Genencor worked together to develop a strain of E. coli that metabolized glucose to a glycerol intermediate that can be converted to PDO. There is interest in using glycerol as feedstock since prices have dropped with the increase in biodiesel production[123].

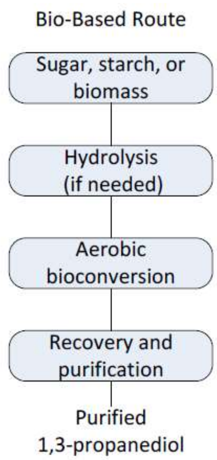

Figure 35: PDO Renewable Process[124]

Market Overview and Potential Products

PDO has stain resistant and durable properties that make it valuable in polyester materials such as PTT, the main product for PDO. Other applications for PDO are de-icing products, engine coolant, heat transfer fluids, polyurethanes, and polyester resins. In cleaning solutions, it is a solvent and enzyme stabilizer and in food applications it acts as a humectant, preservative booster, and stabilizer. PDO is only produced by a few companies so market information is closely held, but it is estimated that market volume is 130,000 MT/yr. and prices are approximately $1,750/MT[125].

Polytrimethylene Terephthalate (PTT)

PTT is a polyester formed by the esterification of PDO and terephthalic acid or transesterification with dimethyl terephthalate. The effective commercialization of this polymer by DuPont may allow PTT to compete with PBT and PET. It is currently being used to make carpet fiber[126].

[122] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[123] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[124] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential
[125] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals
[126] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

Commercialization

DuPont/Tate & Lyle

DuPont and Tate and Lyle announced a joint venture in 2004 to build a plant to produce polymers from renewable materials and specifically to use a fermentation technology to use corn sugar to create PDO. DuPont Tate & Lyle state that their process has a smaller environmental impact, lower operating expense, lower capital investment, and greater sustainability than conventional petroleum processes at the time. DuPont and Genencor worked jointly to engineer a strain of E. coli to ferment glucose instead of glycerol. The conventional methods produced primarily by Shell have proven to be unprofitable and have given way to biobased methods over the last 8 years which have shown that they are more cost effective. DuPont Tate & Lyle has stated that the bio-PDO process uses 40% less energy than conventional methods. They market PDO under two product names – Zemea for personal care, cleaning, and food processing applications and Susterra for industrial applications[127].

[127] Source: duponttateandlyle.com

Succinic Acid

Succinic acid is a dicarboxylic acid, containing four carbon atoms, that has garnered much attention in the bio-based market as a versatile building block. It was included in the 2004 U.S. Department of Energy's 12 Top Value Added Chemicals. Bio-succinic acid is identical in composition to petroleum derived succinic acid whose market size has been limited by its expensive process. Historically, succinic acid was obtained by distilling amber and has been referred to as the "spirit of amber"[128]. The acid has uses in numerous industries including polymers, food, detergents, flavors, and fragrances. It can also be an intermediate to a number of chemicals including 1,4 BDO among others and a near drop-in for adipic acid. Succinic acid has a chemical composition of $C_4H_60_4$.

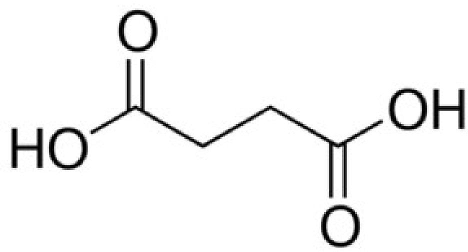

Figure 36: Succinic Acid Chemical Structure ($C_4H_60_4$)[129]

<u>Chemical Synthesis Process</u>

Succinic acid is an important industrial chemical that has been produced from petroleum for many years. The main route to succinic acid from petroleum is through the hydrogenation of maleic anhydride or maleic acid. The process starts with the oxidation of butane, a product of petroleum refining or natural gas processing, and then maleic anhydride or maleic acid is then catalytically hydrogenated to succinic acid[130].

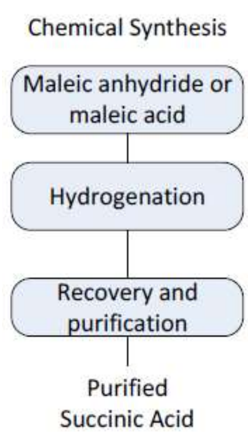

Figure 37: Succinic Acid Chemical Synthesis Process[131]

[128] Source: Wikipedia.org
[129]Source: www.sigmaaldrich.com
[130] Source: Weastra: Determination of Market Potential for Selected Platform Chemical
[131] Source: US DOE EERE: Top Value Added Chemicals from Biomass

Renewable Production Process

Succinic acid can be produced from renewable sources by the biological conversion of commodity sugars, glycerol, or lignocellulosic sugars. Commodity sugars are the feedstocks that are currently being used in commercial operations of today. Bio-succinic acid can be produced from two different methods: a low pH yeast method or via bacterial fermentation[132].

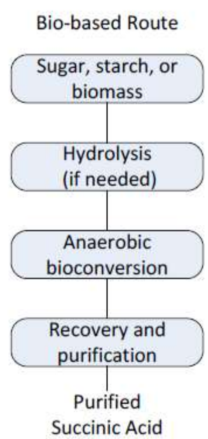

Figure 38: Succinic Acid Renewable Process[133]

Market Overview and Potential Products

The current succinic acid market is estimated to be 50,000 tons and prices are between $2,000 - $2,500/ton[134]. The existing market is small at this point with a focus on specialty chemicals and other niche markets. The process to create succinic acid from petroleum is expensive and that has directed the market towards the higher margin products. Bio-succinic acid is identical in chemical composition and has the ability to be cheaper in production costs if large scale is achieved.

As a platform chemical, succinic acid can be used broadly in a variety of markets, with specialty applications like personal care products and food additives or larger volume markets like plasticizers, polyurethanes, resins, and coatings. The largest applications today are industrial uses in resins, coatings, and pigments followed by pharmaceutical uses and food applications.

132 Source: Weastra: Determination of Market Potential for Selected Platform Chemical

133 Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential

134 Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

Figure 39: Succinic Acid Applications[135]

The focus for bio-succinic acid has been to find a market where it can be a "drop-in" for petroleum chemicals and it has been said that the addressable market can be $7-10B opportunity. The growth opportunities center around succinic acid's ability to be used as a platform chemical to create value-added products like polymers, solvents, and surfactants. The largest market potential for succinic acid is believed to be in BDO, PBS, and polyurethanes. The companies pursuing commercialization are targeting the markets described below for growth moving forward[136].

Functional Replacement for Adipic Acid

Succinic acid can function as a substitute for adipic acid in products such as polyurethanes, resins, and plasticizers. However, succinic acid has competition in the adipic acid market as there are pathways to create adipic acid from biomass; companies are pursuing adipic acid production from fatty acids and glucaric acid also. Replacing Adipic acid is attractive due to its large market size, which was estimated to be 3,000 kilotons in 2015 with over 60% being used in the production of nylons. Besides market size, the main motivation for pursuing a functional replacement for adipic acid is that bio-based companies felt they could produce at lower cost than conventional methods over the long term and that sustainable methods could produce incentives from government programs or greater demand from consumers. Industry stakeholders stated that the market has not accepted bio-succinic acid as a replacement to this point since downstream partners would have to change processes slightly to accommodate the different molecule[137].

[135] Source: Weastra: Determination of Market Potential for Selected Platform Chemical
[136] Source: Weastra: Determination of Market Potential for Selected Platform Chemical
[137] Source: Weastra: Determination of Market Potential for Selected Platform Chemical

1,4 Butanediol (BDO)
Maleic anhydride is a chemical produced from the oxidation of benzene or butane and has a large market volume. Its main use is in the production of unsaturated polyester resins but another large application is in the production of BDO, another chemical highlighted in our report. Succinic acid has a similar structure to maleic anhydride and can function as a replacement in the production of BDO and important derivatives, gamma-butyrolactone (GBL), tetrahydrofuran (THF), and polybutylene terephthalate (PBT). BDO is used in polyurethanes for leather and manufacturing of engineering plastics. A majority of its use though go towards its primary derivative THF, which can be used as a solvent or as starting material for Spandex. Many of the current bio-succinic acid market participants are targeting processes for BDO production to gain access to the 1mm ton market.

Polybutylene Succinate (PBS)
PBS is a newer biopolymer that is biodegradable and has properties comparable to polypropylene. Polypropylene is the second largest polymer so the potential for PBS is very large. It has gained attention since it can decompose into water and CO2. The market is currently small but is expected to increase along with the demand for biodegradable plastics. PBS can be used in food packaging, fibers, textiles, consumer goods, electronics, plastic utensils, mulch films, and diapers. It is produced by combining succinic acid and BDO, thus being an enticing market for both bio-succinic acid and its derivative BDO[138].

<u>Outlook</u>

The market has potential to grow and there are estimates that it will increase to 250,000 tons by year 2020. Industry stakeholders are more conservative in their estimates and believe the growth rate is less than 5% a year at this point. There are promising products that may drive demand in future years as previously mentioned but market acceptance has been slow to this point. The current producers of bio-succinic acid are not running at capacity at this point with BioAmber estimated to be running at 20% while Myriant is idle.

<u>Commercialization</u>
There are a number of companies pursuing the commercialization of renewable succinic acid and all joined the market around the same time in 2009-10.

Reverdia
Reverdia is a joint venture between Dutch company Royal DSM and Roquette Freres out of France. It was created in 2010 for the production and commercialization of Biosuccinium, a sustainable succinic acid. Reverdia started production at a commercial scale facility in Cassano Spinola, Italy in December 2012 to become the first of its kind. The facility has capacity of 10,000 MT annually using a process that utilizes low-pH yeast technology. Reverdia has also announced that they are licensing the technology for businesses looking to integrate renewable succinic acid into their products[139].

Myriant

[138] Source: Weastra: Determination of Market Potential for Selected Platform Chemical
[139] Source: Reverdia.com

Myriant is another company that has been making headway in the renewable succinic acid market. Myriant and ThyssenKrupp Uhde aligned to commercialize bio-succinic acid in 2009 and had produced the product by 2013 with commodity sugar feedstocks in Leuna, Germany. They use a fermentation technology that uses a modified E. coli for the succinic acid production. Myriant also announced the startup of a US based flagship plant in 2013 located in Lake Providence, LA with capacity of 30MM lbs. of biobased succinic acid which was partially funded through a cost sharing agreement of $50MM from the DOE, $25MM from the USDA loan guarantee program, and a $10MM grant from Lake Providence Port Commission. In addition to the project funding, Myriant secured PTT Global Chemical as a strategic partner[140].

BioAmber

BioAmber was created in 2010 as a spin-off from Diversified Natural Products (DNP). DNP originally established a joint venture with French company Agro-Industrie Recherches et Developpements to develop bio-based succinic acid but DNP acquired 100% of the venture and renamed the company BioAmber. In 2013, the Montreal based BioAmber was listed on the New York Stock Exchange under symbol BIOA with an $80MM IPO. In 2015, the company began operation at 30,000 MT commercial facility in Sarnia, Ontario that cost $141MM, the largest succinic acid plant in the world. The Sarnia plant uses corn starch as a feedstock in their fermentation process but has flexibility to use any first generation sugars and their long-term goal is to move to cellulosic sugars. BioAmber plans to build a second plant in North America to produce 1,4-BDO, tetrahydrofuran (THF), and succinic acid. It will have capacity of 100k tons of BDO/THF and 70k tons of succinic acid. The company states that they have already signed take or pay contracts for 80% of capacity and will look to construct in Louisiana or again in Sarnia[141].

Succinity

Succinity is a joint venture between BASF and Corbion that began in 2009. The company is headquartered in Dusseldorf, Germany and has a 10,000 MT production facility in Montmelo, Spain that came online in 2014. The Succinity process converts either a sugar stream or glycerol to succinic acid by using a bacterium strain engineered and under patent by BASF[142].

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[140] Source: myriant.com and company interviews

[141] Source: bioamber.com

[142] Source: succinity.com

Xylitol

Xylitol is a sugar alcohol containing 5 carbon atoms. The clear solid is also referred to as wood or birch sugar and is found naturally in the fibers of various fruits and vegetables[143]. Xylitol has received interest globally in uses as a sweetener and has a chemical composition of $C_5H_{12}0_5$.

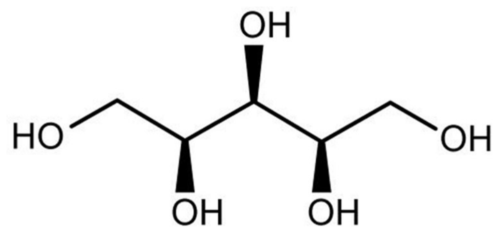

Figure 40: Xylitol Chemical Structure ($C_5H_{12}0_5$)[144]

<u>Petroleum Production Process</u>

There are no petrochemical alternatives for Xylitol, it is produced solely by renewable methods.

<u>Renewable Production Process</u>

Xylitol can be produced from chemical or microbial processes. The more common method is to use hemicellulose from hardwoods or corncobs and hydrolyze it to xylose. The xylose is then catalytically hydrogenated into xylitol. The other method involves fermentative or biological processes in bacteria, fungi, or yeast to produce xylitol. It is reported that this method has issues with fermentation of the lignocellulosic streams and the cost of xylitol separation from the fermentation broth[145].

<u>Market Overview and Potential Products</u>

Xylitol has current and potential applications in food, odontological, and pharmaceutical markets. The xylitol market volume is estimated to be 160,000 MT a year and prices between $3,000 - $3,900/MT. It is commonly used as a sugar substitute and contained in "sugar-free" chewing gum and other candies. Xylitol has little effect on blood sugar and insulin, so the harmful effects of sugar do not apply and is considered a diabetic sweetener. It also can be considered a weight-loss friendly sweetener as it has 40% less calories than sugar. Xylitol is also used in chewing gum and toothpaste for its properties to prevent tooth decay and its use can significantly reduce the rate of cavity development. As a medicine, xylitol is given to children to prevent ear infections[146].

<u>Commercialization</u>

DuPont Danisco
Danish company, Danisco bought Finland's largest xylitol producer in 1999 to get into the business and within the next decade owned plants in Finland, the US, and China to be the world's largest xylitol

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[143] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals
[144] Source: www.sigmaaldrich.com
[145] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals
[146] Source: European Commission: From the Sugar Platform to Biofuels and Biochemicals

producer. The Danish firm produces xylitol by tapping into a waste stream from the pulp and paper industry for feedstock. They use a hydrogenation process to produce xylitol from the xylose as opposed to other companies that use acid hydrolysis or fermentation. In 2011, Danisco was acquired by DuPont for $5.8B and now markets their xylitol by the name Xivia[147].

S2G Biochem

S2G Biochem is a chemical conversion company that produces xylitol and bio-glycols from forestry and agricultural residue. Vancouver based S2G has a pilot plant in operation since 2012 and two research labs in the pacific northwest. In October 2016, S2G announced an agreement with Mondelez International to receive financial support for development of their first commercial facility for xylitol[148]. The location of that facility was announced in 2017 and would be part of the biorefinery cluster in Sarnia with an investment by Bioindustrial Innovation Canada. Construction will begin in 2018 on the $20MM xylitol plant that will produce 2,000 MT a year[149].

[147] Source: Danisco.com
[148] Source: S2GBiochem.com
[149] Source: Biofuels Digest: S2G BioChem Building Advanced BioRefinery in Sarnia: Production of Xylitol to Begin in 2018

Chemical Rankings

Ascendant assembled a ranking system to compare and contrast the profiled chemicals to filter the chemicals which warrant further analysis, continued interest, and should be watched closely as the industry continues to evolve. The ranking system is based on four success factors on a scale of green to red derived from insight gained in conversations with industry experts and were also used to derive our initial list. The four success factors are whether it's a platform chemical, whether it contains an oxygen molecule, does the chemical or derivative compete directly with petroleum products, and whether there has been significant market interest.

Chemicals	Success Factors			
	Platform Chemical	Oxygen Molecule	Not Direct Competitor with Petro	Significant Market Interest
1,4 Butanediol (BDO)	Green	Green	Red	Green
Furans (Furfural, HMF, FDCA)	Yellow	Green	Green	Green
Glucaric Acid	Green	Green	Yellow	Red
Isoprene	Red	Red	Red	Green
Itaconic Acid	Green	Green	Green	Red
Lactic Acid	Yellow	Green	Green	Green
Levulinic Acid	Green	Green	Green	Red
Para-xylene	Yellow	Red	Red	Green
1,3 Propanediol (PDO)	Yellow	Green	Green	Yellow
Succinic Acid	Green	Green	Yellow	Green
Xylitol	Yellow	Green	Green	Green

- Platform Chemical
  - Green – 3 or more derivatives and various direct uses
  - Yellow – Less than 3 derivatives and a few direct uses
  - Red – Mostly used in one market
- Oxygen Molecule
  - Green – The chemical has an oxygen molecule
  - Red – The chemical does not have an oxygen molecule
- Not a Direct Competitor with Petroleum
  - Green – Not a direct competitor with petroleum derived products
  - Yellow – Can't be made from petroleum but targets markets that are dominated by petro-products
  - Red – Direct drop-in for petro-product
- Significant Market Interest
  - Green – Significant attention from large companies and multiple producers targeting chemical
  - Yellow – Some Interest and production by one large company
  - Red – Producers in the space but market is early stage or unclear

Figure 41: Chemical Rankings Based on Success Factors

For the platform chemical success factor, the rankings are based on whether the chemical can be considered a building block for a biorefinery model. The rankings took into account how many other chemicals and derivatives could be potentially reached from the chemical as a starting point and also considered the amount of potential direct uses in the marketplace. This success factor represents flexibility for the biorefinery. The chemicals that were given a yellow ranking had fewer derivatives and direct uses but were mainly categorized as such since one main market will determine its overall growth.

In the case of p-xylene and lactic acid, growth will ultimately be determined by growth of renewable PET and PLA respectively.

The success factor for being a competitor with a petroleum product is important as it determines whether it is a drop-in chemical or a novel product/functional replacement product. The three red rankings are identical products to petroleum products and may have difficulty competing in price with its competitors unless produced on a large-scale. Glucaric acid was given a yellow ranking as it is considered a novel product but a main market would be to produce adipic acid which will compete with petroleum products. Succinic acid falls in the middle also since it can be produced by chemical synthesis and its derivative BDO can as well, but it acts as a functional replacement for adipic acid.

The significant market interest factor accessed the amount of companies pursuing production as well as end product users who have shown interest in a bio-product using the chemical. The markets for itaconic, glucaric, and levulinic acids are unclear and small at this point, while they have some producers but are producing at small scale currently. The market situation for these three can change quickly if they gain market acceptance for products they are developing. PDO is the only chemical that falls in the yellow category as it is being produced by a large company in DuPont Tate & Lyle but the market is relatively small at this point.

<u>Chemical Market Size and Price</u>

Ascendant compiled the market size and market price of the chemicals in the following table. Many of the markets are very small with high prices since most uses are in niche markets currently. The larger markets like BDO, isoprene, and para-xylene are mostly derived from petroleum processes with very little of the volume coming from biobased methods.

Chemicals	Current Market Size and Price	
	Market Size	**Price**
1,4 Butanediol (BDO)	2,500,000 MT	$2,300 - $2,400/MT
Furans (Furfural, HMF, FDCA)	Furfural: 270,000 - 300,000 MT HMF: 100 MT FDCA: 45 MT	Furfural: $1,000 - $1,450/MT HMF: $2,600+/MT FDCA: N/A
Glucaric Acid	3,000 - 5,000 MT	$3,000/MT
Isoprene	850,000 MT	$2,000/MT
Itaconic Acid	41,000 MT	$1,800 - $2,000/MT
Lactic Acid	472,000 MT	$1,500/MT
Levulinic Acid	7,000 MT	$5,000 - $8,000/MT
Para-xylene	35,000,000 MT	$800/MT
1,3 Propanediol (PDO)	130,000 MT	$1,760/MT
Succinic Acid	50,000 MT	$2,000 - $2,500/MT
Xylitol	160,000 MT	$3,000 - $3,900/MT

Figure 42: Current Market Size and Price of Chemicals[150]

Given the small market size and need for significant scale to reduce operating and capital costs, targeting any of these markets currently is difficult. The success of these biochemicals will depend on breaking into new addressable markets and thus far market acceptance has been minimal.

Outcome of Rankings

After assessing the chemicals based on the success factor criteria, four chemicals came out more favorably than the rest: furans, lactic acid, succinic acid, and xylitol. The characteristics that allowed them to rank higher on the list are included in the table below.

Top 4 Ranked Biochemicals

	Flexibility in Products/Pathways (Platform Chemical)	Product/Derivative Competition with Petroleum Products	Extent of Commercialization and Market Interest
Furans	Furfural has various derivatives and uses, mostly as a solvent. HMF has one derivative in FDCA which is primarily used as a replacement of terephthalic acid to create PEF	Furans can't be made from petroleum processes. FDCA is a functional replacement for terephthalic acid to make a new polyster in PEF	Furfural and HMF are small markets, with the majority of interest coming from FDCA. Companies that use PET bottle like Coca-Cola and Danone have significant interest in PEF bottles
Lactic Acid	Lactic Acid has direct uses but its potential as a bio-product is dependent on PLA	Lactic acid is only made form renewable processes and PLA is a novel product with different properties than other plastics	PLA has garnered plenty of interest from retailers to meet sustainability goals since it is biodegradable. Commercialization is being pursued by 3 prominent producers
Succinic Acid	Succinic acid has many uses and derivatives in industrial, pharmaceutical, food, and other industries. It is the prime example of a platform chemical	Succinic acid is a direct competitor with petroleum products as is its derivative BDO. It also acts as a functional replacement to adipic acid	Succinic acid has been a hot story in the bioeconomy. 4 companies with prominent investors pursued commercialization at the same time
Xylitol	Xylitol has uses in food, odontological, and pharmaceutical markets. However, its primary market is as a "sugar free" substitute for gum and candy	Xylitol can only be made from renewable sources and does not compete with petroleum products. However; it does compete with commodity sugars.	Xylitol has gained interest as a sugar substitute and is produced by DuPont Danisco. S2G Biochem is also pursuing commercialization by building a plant in the Sarnia Bio-cluster

Figure 43: Outcome of Rankings: The Top 4 Based on Success Factors

Although the four chemicals have potential and warrant attention going forward, their promise has not been fully realized. FDCA and PLA for example have novel qualities but have yet to gain market acceptance over other plastics. While xylitol, lactic acid, and furfural show potential to be made from hemicellulose which can be a great benefit to a biorefinery, but their markets are small at this point. This shortened list does not necessarily preclude the others either. The bioeconomy changes quickly as new advancements in technology makes different markets come into the spotlight.

The following chemicals did not rank as highly but have interesting situations worth noting:

Para-xylene did not rank as highly since it does not contain an oxygen molecule and is a clear example where it will compete with petroleum products. However, pX most likely has the highest amount of interest in this group since it has 5 different companies with differing technologies pursuing it from renewable methods and large companies like Coca-Cola and Pepsi investing in the development of renewable PET.

Itaconic acid and levulinic acid fit the criteria for 3 of the 4 success factors being platform chemicals, containing oxygen, and not competing directly with petroleum products. These two chemicals are early in

[150] Source: NREL: Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential; European Commission: From the Sugar Platform to Biofuels and Biochemicals; Tecnon OrbiChem: Chemical Business Focus, Issue Number 33, 5/31/16

the process for developing markets and their situation could change quickly if a market develops. Levulinic acid has promising potential as an additive for heating oil or as a precursor for jet fuel. These are large markets where further development could open up an interesting opportunity.

MARKET OPPORTUNITIES AND CONSIDERATIONS

The North American pulp and paper industry has been in decline in recent years and mills competing in a shrinking market are being forced to close or lay off workers. There are two driving forces leading to the decline: the first is the decrease in use of printing and writing paper and the other is the competition from pulp mills in Asia and South America[151]. Paper will never completely disappear from our society but it will be a smaller market than it's been as we continue to evolve into an electronic society.

Maine's once robust pulp and paper industry has been no exception to this trend and has felt the decline. The state has seen the closing of six pulp and paper mills and two biomass electricity plants since 2014. This has led to a decrease of $1.3 billion in economic impact for Maine's forest products industry and loss of over 5,000 jobs[152]. Stakeholders in Maine's $8.5B industry and around the pulp and paper global market are looking to increase value in their existing infrastructure. In order to remain viable, many are exploring increasing value by producing bioenergy and biomaterial along with the wood, pulp, and paper products as a path forward.

Biorefinery Model

The business model that has been proposed is the forestry biorefinery. A biorefinery is defined by IEA Bioenergy Task 42 as "the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)". The concept is comparable to the petroleum refinery model which produces multiple fuels, chemicals, and other products from petroleum utilizing the scale and infrastructure for improved economics. Bio-products can be produced in individual processes but the integrated biorefinery processes with the ability to produce various bio-products and bioenergy can more efficient for the valorization of biomass resources. The biorefinery is being explored as a practical way to improve the economics of biomass to energy or paper products by introducing high value chemicals or other products. For example, a biorefinery may produce one or more small market, high value chemicals and a large market, low value commodity product like fuel or pulp, while also generating power for its own use or sale. The high value products add profitability, the high volume product allows throughput and continuous use of infrastructure, and the power production lowers energy cost for the facility. Although the concept has been explored for a while and certain facilities may fit the description, the biorefinery model has not been completely realized.

The pulp and paper industry is mature and produces low-margin commodity products but has the ideal infrastructure, experience, and resources to be successful in utilizing a biorefinery concept. The pulp mills have on-location feedstock, proximity to active forestry regions, necessary utilities, access to waste streams, and waste treatment capabilities. The mill owners could potentially increase revenues while continuing to produce their wood, paper, and pulp products. By adding value-added byproducts, the forestry companies have an opportunity to diversify their revenues outside the pulp and paper industry.

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[151] Source: Biofuels Digest: Bounding Maine: Top 10 Companies Targeting Maine's Forest Resource for Higher-Value Apps

[152] Source: Mainebiz: Road Map for Strengthening State's Forest Economy Sets Nine Priorities

Pulp and paper is the world's largest nonfood biomass collection system[153], an attractive synergy for a biorefinery model. The existing mills will have on-site feedstocks but forestry practices also leave behind wood residuals in the forest. These residuals represent 15-20% of total tree mass and are not currently utilized or often collected[154]. Renewable technologies for bio-products can utilize the existing pulp and paper feedstock collection system or explore ways to collect the residuals for feedstock. The economics of a forestry biorefinery model are more attractive if the process can utilize waste streams from existing processes and would result in near zero feedstock cost.

Biorefineries in Production

Lenzing Biorefinery – Lenzing, Austria

Lenzing AG is a fiber innovation company whose main businesses are textiles, nonwoven cellulose fibers, and polymer plastics. The company is based in Lenzing, Austria but has production facilities in many major markets. Their main facility in Austria produces 250,000 tons of cellulose fibers and 290,000 tons of pulp annually from beech wood feedstock. However, the facility has been considered a biorefinery since they built their "vapor condensate extraction plant" in 1983. The biorefinery produces acetic acid and furfural as its main two coproducts and in the last 34 years, Lenzing has produced over 470,000 tons of acetic acid and 110,000 tons of furfural. The company recently received the biobased product label from the USDA for their coproducts[155].

DuPont Danisco has a xylose producing plant collocated in Lenzing that takes the black liquor stream from the pulp and paper mill and extracts the xylose. The remaining side stream is returned to the pulp and paper plant for energy production and xylose is sent to another Danisco plant to produce xylitol[156].

UPM Lappeenranta Biorefinery – Lappeenranta, Finland

UPM's biorefinery is located in Lappeenranta in southern Finland. It is the first commercial scale biorefinery to produce wood-based diesel and naphtha. UPM built the 175MM Euro facility in 2012 and located it next to their 310,000 MT Kaukas pulp and paper mill. The biorefinery produces renewable diesel called BioVerno and naphtha from crude tall oil, a residue of the pulping process, in a 3-step process of pretreatment, hydrotreatment, and fractionation. The facility produces 100,000 MT of biofuel a year.

[153] Source: Bajpai, Pratima: Biorefinery in the Pulp and Paper Industry
[154] Source: Bajpai, Pratima: Biorefinery in the Pulp and Paper Industry
[155] Source:Lenzing.com
[156] Source: Danisco.com

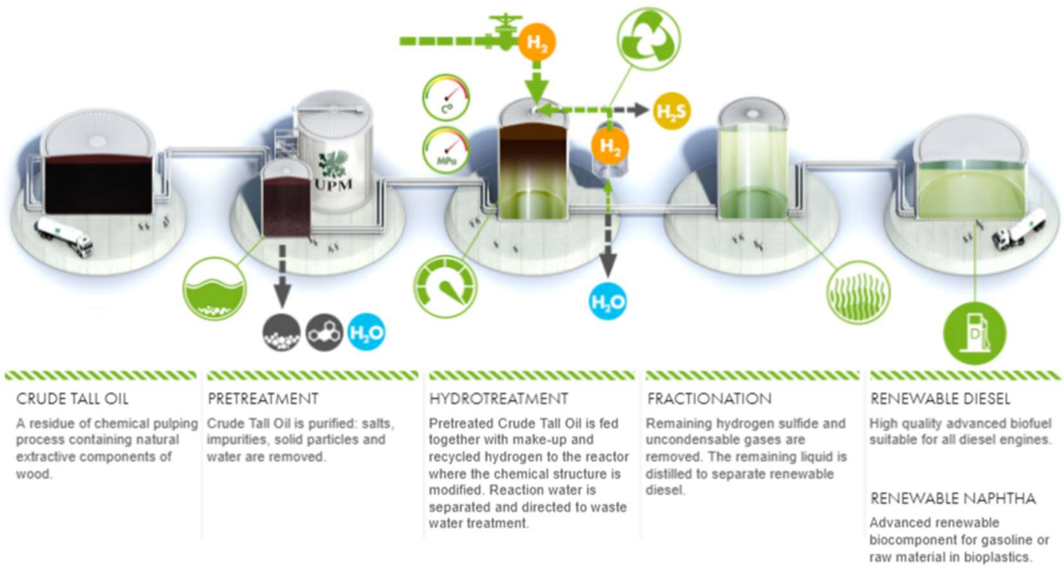

Figure 44: UPM Biorefinery Technology: Biodiesel/Naphtha[157]

Sarnia-Lambton Biohybrid Chemistry Cluster – Ontario, Canada

The Sarnia/Lambton area has been and still in some ways is a petroleum community with many multinational companies located there. The oil community was booming until eventually, in the 1990's, refineries began to close due to increases in automation and outsourcing. A breaking point as reached when a TransAlta ethylene pipeline from Alberta was shut down. This caused Dow Chemical to announce they would cease the operation of their Canadian headquarters in 2006 and Sarnia lost 2500 high paying jobs. The community used this as a wakeup call to act or they would potentially lose other large operations. Today, there are still 19 petrochemical plants in the Sarnia area that produce products from crude oil, natural gas, and ethane[158]. The initiative for the bio-cluster spearheaded by Bioindustrial Innovation Canada was not intended to displace the petroleum infrastructure but to complement it. The petroleum industry in the area is still declining slowly due to computerization and the bioeconomy is being built to offer new alternatives, jobs, and grow the community again including local agriculture[159].

The Sarnia-Lambton Biohybrid Chemistry Cluster was born to utilize the existing process infrastructure, providing proximity to both oil and bio-based feedstocks, and access to markets by rail, road, and deep water port. There are dozens of companies located in the cluster currently, here are a few of the companies with bio-based technologies.

BioAmber – built their first commercial scale plant for production of biobased succinic acid. They have the ability to use first or second generation sugars.

[157] Source: UPMbiofuels.com
[158] Source: ACCN (Canadian Chemical News): Petrochemical Heartland
[159] Source: industry interview

Comet Biorefining – plans to build a commercial scale facility to produce cellulosic sugars from corn stover and other renewable materials. They plan to supply BioAmber and other manufacturers with glucose from cellulosic sugar.

Suncor Energy Products – operates Canada's largest ethanol facility out of this location. They have capacity to produce 400MM liters annually.

BIOX – renewable energy company with a network of production facilities including two biodiesel plants.

ARLANXEO Canada Inc.- world's largest producer of synthetic rubber. They have also shown interest in sustainable processes by investing $10MM in BioAmber for development of renewable plasticizers.

The Cellulosic Sugar Producers Co-operative – Ontario farmer co-operative to supply crop residue materials for cellulosic sugar production, primarily for Comet.

Origin Materials – announced they plan to build a demonstration facility in Sarnia by the end of 2018. They have a process to produce renewable para-xylene and PET from biomass.

S2G Biochem - announced they plan to build their first commercial xylitol plant with support from Mondelez on the project. The plant will be $20MM and will produce 2,000 MT/yr. from forestry and agricultural residue[160].

Globally, there are a few examples of biorefineries that have been successful either by one large company producing multiple products to utilize more of their biomass or a cluster of companies sharing the industrial infrastructure. The bio-economy can look at these examples to learn lessons about what went right and wrong in those scenarios to further build on the model. In examining biorefinery scenarios and speaking with stakeholders in Sarnia, Ascendant has compiled the following lessons and associated best practices.

Lessons from Existing Biorefineries

Lessons Learned	Best Practices
It is beneficial to "grow green" around the commodity infrastructure, not compete with it	The existing infrastructure is in place because of the commodity process. Make sure renewable processes fit as seamless as possible without disrupting the commodity operations
Marketing for the opportunity is very important to attract investment and technology companies	The region's image can be a strong marketing tool. Start the marketing campaign early and seek professional marketing support
All parts of the community must be aligned 100% towards the same goal (incl. rural community, government, and business)	Ensure that all parties are consulted and will benefit from project from early stage to help attract positive attention, momentum, and ultimately investment
Flexible biorefineries which produce high value products and utilize most of the biomass are important for profitability	Utilize multi-product streams, focus on technology with high biomass utilization, and emphasize high value products early
Increased production of one product decreases production of another	Look at local economics of all products and plan contractual agreements for changing environments
Many unforeseen problems arise during scale-up of a technology	Emphasis should be placed on risks of scale-up; data validation and pilot stage performance should be scrutinized prior to design of integrated project

[160] Source: www.sarnialambton.on.ca

Figure 45: Lessons and Best Practices from Existing Biorefineries

Considerations for Maine

Maine is positioned well to attract investment to the state and has an opportunity to create a successful biorefinery model with the existing infrastructure. Its important forestry industry has an interesting dynamic today as the hardwoods are in high demand, the tissue and sawlog markets are doing well, and yet the pulp and paper markets are struggling[161]. The state has seen 5 mills close in the last 3 years and the forest-related employment has been cut in half since the mills were all running strong[162]. However, the combination of infrastructure, feedstock, and workforce provides an attractive opportunity for the bio-economy. Stakeholders around the industry have taken notice and have been outspoken in our conversations about the potential.

Maine has 17 million acres of forestland and the structure for the collection of the source of biomass. The mills that are currently running have tons of residual chips, sawdust, and waste streams that can be tapped into with the right technology and end market. The shuttered plants are valuable brownfield locations that are already setup for utilities, equipment, and waste treatment. Maine also has the workforce with the experience and know-how in the forestry industry and in these same plants. The infrastructure is enticing to the companies looking at renewable chemicals and products.

The marketing effort has also been important to bring momentum and interest for the biobased investment effort. BioBased Maine has been vocal and present in the top bio-based publications and conferences while Maine Born Global Challenge has also brought attention to the cause. In concert with the marketing effort, the government has shown an interest and willingness to get involved which will be important to the industry. Governor LePage recently spoke at the Advance Bioeconomy Leadership Conference to let the industry know that Maine is open for business and there are plans for the state to provide equity funding[163]. Maine has the right combination of factors that the bioeconomy is looking for and is now primed to find the right fit for investment. As Biobased Maine looks for the right partner to match with the structure in place, Ascendant has identified the following considerations from our conversations with industry stakeholders.

- **Flexibility of the model and chemicals**

A key aspect of a biorefinery is the ability to produce multiple products. To be able to sustain through different market conditions, a biorefinery model will need flexibility with their multiple product streams. The petroleum refinery is a good analogy as it has specifications for over 2,000 individual products.

[161] Source: Biofuels Digest: Bounding Maine: Top 10 Companies Targeting Maine's Forest Resource for Higher-Value Apps
[162] Source: Mainebiz: Road Map for Strengthening State's Forest Economy Sets Nine Priorities
[163] Source: centralmaine.com: LePage invites bio-based business to call Maine home

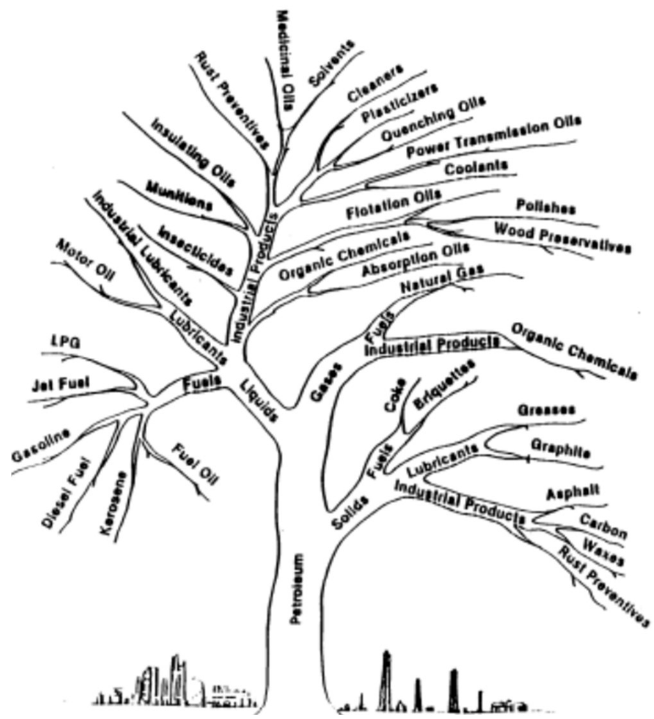

Figure 46: Pathways from Petroleum[164]

The petroleum refinery can route its different intermediate feedstocks to multiple units of the refinery to produce different end products as the economics determine. Now as one industry stakeholder mentioned, it can be costly to change direction and end products. A large operation such as a refinery does not change direction overnight but by concentrating on multi-product streams they can shift focus over time to evolve with the market conditions. A biorefinery can use the same multi-product stream strategy but also can focus on platform chemicals that can be directed towards multiple markets. A platform chemical can be produced and used as starting material for different derivatives, allowing the biorefinery to target various end markets and products as the bioeconomy continues to adapt to consumer needs.

Focusing on a platform chemical will be important for the biorefineries' growth strategy as well. The difficulties and high cost of scale-up is a common story in the bioeconomy. Companies are often unable to predict problems that can arise during commercialization which can be costly and scale-up in the bioeconomy has been difficult to fund regardless. A biorefinery can use a platform chemical to focus on niche, specialty markets to get off the ground and generate revenue. As the operations are streamlined and smoothed, the biorefinery can eventually shift focus to compete in larger volume markets. The biorefinery can use the flexibility to choose when and how to compete with low cost petroleum processes when the economics are right.

- **Ability to plug into the existing infrastructure**

In order for new bio-chemicals or intermediates to function as drop-ins or replacements in existing products, the downstream partners' process should be affected as little as possible as any process changes will add cost on their end. An example from industry stakeholders was the situation in the current succinic

[164] Source: NREL: Encouraging the Development of Biorefineries PowerPoint

acid market. BioAmber touts the ability of their process to use either conventional or cellulosic sugars to produce succinic acid. This capability is predicated on equal quality between the two sugars and economics helping in their decision on which supply to use. Bio-succinic acid producers had a false assumption in this regard about their own product and its ability to function as a replacement for adipic acid in the market. It was assumed that since bio-succinic acid could be used adequately in products instead of adipic acid that the market would be willing to switch quickly. Although the end products may have the same functionality and performance, the downstream companies do have to change their process slightly and a change in the industry and thus succinic acid growth will take time to develop.

The idea of a seamless fit into existing infrastructure should be applied by biorefineries not only for downstream processes but with upstream partners as well. As previously mentioned in the best practices from existing biorefineries, the infrastructure for a biorefinery exists because there is a commodity process such as a pulp and paper mill. The added technology for bio-products should fit seamlessly into the commodity process to not affect the day to day operations. The biorefinery should be looked at as an added-value for the pulp mills instead of a hindrance that negatively affects their main operation.

- **Ability to use biomass to a high degree**

The biorefinery will be most successful and profitable if it can utilize as much of the biomass as possible. A successful integration of biorefinery operations with mill operations starts with the feedstock choice for the biorefinery. Different models focus on various feedstocks such as the residuals left from the forestry operations or waste from technologies on-site at the mill. Residuals require greater operational and logistics planning but are promising from a sustainability viewpoint. The on-site waste streams could improve the economics of a biorefinery but technology may need to be further developed to handle difficult wastes like the black liquor from a pulp mill. Although there have been recent developments in technologies to utilize the lignin and hemicellulose from the black liquor or to extract earlier in the process. Biorefinery process options such as hemicellulose preextraction, lignin precipitation, and black liquor gasification are emerging to address utilization of this difficult feedstock[165].

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[165] Source: Bajpai, Pratima: Biorefinery in the Pulp and Paper Industry

CONCLUSIONS

Ascendant performed market research and interviewed various industry stakeholders to assess the overall trends in the biochemical market and promising renewable chemicals with near-term market potential. We narrowed down from the hundreds of potential renewable chemicals to a short list of promising chemicals with market potential and possible synergies with Maine's infrastructure. Using this shortened list, Ascendant further categorized the chemicals based on critical success factors to be successful in the future bioeconomy.

Through the study, the common theme was that the markets are still developing and the companies are creating technology to pursue various pathways. It remains to be seen what technologies and chemicals will ultimately succeed in the long term. The profitable renewable chemicals require a balance of production, market size, and selling price.

In our conversations with industry stakeholders, we picked up valuable insight into approaches to consider when designing a business model and evaluating how to integrate the infrastructure with biobased technologies.

- The renewable chemical technologies should start with the end markets in mind. The pathways should be determined by what the market wants in terms of products and exact specifications. A process technology company will have greater assurance of market acceptance by confirming expectation and requirements on the front end.

- Both the model and product streams should have flexibility. A platform chemical allows a company to build a business plan around a niche market to sustain in the short term and expand into larger volume markets as the process is streamlined and scale-up is achieved.

- The process technology should be able to fit seamlessly with the existing commodity infrastructure. The pulp and paper operations will see the benefit of the synergies the bio-process provides as long as it doesn't change or negatively affect their process.

Maine can use the criteria, short list, and considerations provided by Ascendant to assess how these chemicals overlap with the existing infrastructure to find an optimal combination. A narrower focus and criteria when monitoring the biobased chemical market will allow Maine to act once the markets and technology reach defined critical milestones.