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The U.S. Biomanufacturing Economy

Value Added, Supply Chains, Cost, Sustainability, and Efficiency

Douglas Thomas

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Abstract

This report estimates biomanufacturing (manufactured products made of biomaterials) and advanced biomanufacturing (products manufactured using activities that grow biological molecules and materials along with activities that alter biological material using non-mechanical means) value added in ways that make it consistent with estimates of U.S. GDP. Direct advanced biomanufacturing is estimated as being $94.6 billion annually while total direct biomanufacturing is $438.8 billion annually. When including supply chain and other indirect value added, the total biomanufacturing industry is $1363.8 billion and advanced biomanufacturing is $259.9 billion. These estimates include biomanufacturing products that are excluded from estimates of the bioeconomy made by other organizations and/or individuals. For instance, a report by the National Academy of Sciences defines the bioeconomy as that being "driven by research and innovation in the life sciences and biotechnology," which tends to exclude production of many food items that are included in this report's estimates. Other U.S. estimates differ from estimates of GDP and value added. For instance, a bioeconomy estimate can significantly exceed relevant GDP or value added estimates. This report uses the EPA TRACI measures to evaluate the environmental impact associated with the production of products in the bioeconomy. As calculated using NIST's Manufacturing Cost Guide, the production of biomanufacturing goods accounts for 43 % of the total environmental impact resulting from economic activity in all U.S. industries while the production of advanced biomanufacturing goods is 6.4 %. This report also examines the assets, material flow time, fuels, and electricity used in biomanufacturing.

Keywords

manufacturing; biomanufacturing; bioeconomy; value added; sustainability; efficiency; energy; flow time.

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Executive Summary

There are two general definitions of the bioeconomy. A broader definition is found in the European Union and a narrower one found in the United States. For this report, the broad definition, which amounts to biomass production and conversion, is used to identify total biomanufacturing while the narrow definition, which largely includes growing and refining biomaterial, is used to identify advanced biomanufacturing. This report discusses methods for identifying areas with the potential for significant economic impact through the advancement of measurement science. Impacts might be realized as cost savings, environmental impact reduction, increased income/profit, or increased utility. Additionally, it measures the value added of the entire biomanufacturing industry using methods consistent with those used to estimate U.S. GDP, as estimated by the Bureau of Economic Analysis (BEA). The advantage to estimating the bioeconomy in these terms is that it avoids double counting the value of production and is consistent with widely accepted and cited measures of economic activity. The report estimates the environmental impact (measured based on EPA's TRACI methodology), assets used, flow time of production, fuels and electricity used, and opportunities for efficiency improvement for the biomanufacturing and advanced biomanufacturing industries.

High Impact Opportunities: This report identifies two types of technological advancements for the bioeconomy that could yield three different types of impact. There are (1) advancements that improve existing processes and (2) those that significantly alter or create new processes. These advancements can result in the (1) reduction of costs/losses, (2) improvement in product quality/performance, and/or (3) reduction of negative externalities. Achieving the different types of advancements can involve different approaches to identifying high impact research. Areas of potential high impact research can be identified using investment analysis combined with best practices in forecasting and prediction, including the following practices:

- Ensure that the question is refined and logical
- Avoid overweighting extraneous information
- Be aware of one's knowledge boundary
- Break the problem into manageable sub-problems and utilize known data
- Be aware of expert's knowledge boundary
- Generate testable predictions and forecasts
- Utilize the insight of teams, surveys, or other groups of people

Value Added: This report estimates that 2019 U.S. biomanufacturing (i.e., biomass producing and converting industries) value added is $438.8 billion and advanced biomanufacturing (i.e., growing and/or altering biological material with specialized equipment often through non-mechanical means) is estimated to be $94.6 billion calculated using BEA data, consistent with methods to calculate U.S. GDP, as shown in Table 0.1. When including indirect value added (e.g., supply chain items), biomanufacturing is $1363.8 billion and advanced biomanufacturing is $259.9 billion. These provide a more encompassing view of the industry than previous estimates made by the National Academy of Sciences (Connely et al. 2020) and the USDA (Daystar et al. 2020), where the former specifies that it excludes fuels, pharmaceuticals, and a selection of other industries. The latter is based on estimates that differ from the primary values used to measure

GDP (i.e., BEA value added). The estimates provided in this report utilize data organized by NAICS code, which does not completely adhere to the definitions of bioeconomy and advanced bioeconomy; therefore, this data is combined with other data and methods to parse out the bioeconomy.

Environmental Impact: As calculated using NIST's Manufacturing Cost Guide, based on EPA's TRACI measures ('environmental impact'), the production of biomanufactured goods accounts for 43 % of the total environmental impact resulting from economic activity in all U.S. industries, measured as a weighted composite of twelve types of environmental impact, while the production of advanced biomanufactured goods is 6.4 %, as seen in Table 0.1. For the former, food manufacturing (i.e., *NAICS 311*) accounts for the bulk of the impact, which includes the associated agricultural activities. For the latter, much of the impact is in *NAICS 32519 – Other basic organic chemical manufacturing,* which includes biofuels.

Assets and Flow Time: As seen in Table 0.1, the NAICS codes for advanced biomanufacturing have a high level of depreciable assets per dollar of value added, ranging between less than the 1st percentile to the 23rd percentile among all manufacturing, where lower percentile means more assets per dollar of value added. The percentile is a comparison of all manufacturing NAICS codes. Either a large volume of assets and/or very costly assets are required for advanced biomanufacturing. Additionally, the work in process time for pharmaceutical and medicine manufacturing is high with percentiles as low as 5.8 % where lower means longer flow times and more capital is consumed per unit of production.

Fuels and Electricity: As seen in Table 0.1, a number of advanced biomanufacturing industries have a relatively high level of energy consumption, compared to others in the sector, including *ethyl alcohol manufacturing, cyclic crude intermediate and gum and wood chemical manufacturing,* and *other basic organic chemical manufacturing*. These industries might benefit from energy saving efforts.

Efficiency Improvement for Current Processes: Utilizing data from the Department of Energy's Industrial Assessment Centers (IAC), an investment analysis of the recommendations made by IACs reveals areas where there might be high economic returns from efficiency investments often focused on energy efficiency. For example, for the highest 5 % economic returns (measured in net present value) of recommendations to establishments in *NAICS 325190 – Other basic organic chemical manufacturing* include those regarding thermal systems (e.g., heat recovery) and electrical power management (e.g., avoid peaks). For *NAICS 325400 Pharmaceutical and medicine manufacturing*, thermal systems (e.g., heat recovery); motors; building heating, ventilation, and air conditioning; contaminants; and waste disposal were among those in the top 5 % of net present value from investments.

Data Needs: A number of data gaps exist in regard to understanding the costs and losses associated with biomanufacturing. These gaps include data on lost batches, supply chains, data/communication errors, feedstocks, goods inventory, machinery maintenance, reprocessing, changeovers, environmental impacts, redundancy, cyber security, developing new products, and in identifying biomanufactured goods. These data gaps might be filled with better ways to identify bio-based goods, including industry specific surveys. There might be literature on some of the data gaps listed; however, an encompassing survey of the literature related to all biomanufactured products along with the different types of missing data is beyond the scope of this report.

Table 0.1: Summary of Estimates: Value Added, Environmental Impact, Assets, Flow Time, and Fuels

		2020 ASM Data	2019 Man. Cost Guide Estimates (Based on BEA Data)					
Description	NAICS	Value Added ($Billion)	Value Added ($Billion)	Total Direct and Indirect Value Added	Environ. Impact (percent of U.S. Impact)	Depreciable Assets per Dollar of Value Added: Percentile (Higher = Better or fewer assets per $ of value added)	Work-in-process flow time Percentile (Higher = better or shorter time)	Purchased fuels per dollar of value added, percentile (Higher = better or less cost)
Manufacture of food products	311	324.5	155.5	702.1	27.4	52.7	83.9	22.0
Advanced Biomanufacturing of food		9.0	4.3	19.4	0.8	-	-	-
Manufacture of beverages	3121	55.0	38.8	121.0	2.5	37.9	7.0	46.1
Advanced Biomanufacturing of beverages/Tobacco	312	4.0	2.8	8.8	0.2	-	-	-
Manufacture of tobacco products	3122	43.1	45.7	61.8	0.6	99.5	68.1	94.9
Manufacture of textiles	313, 314	5.7	4.5	12.2	0.2	-	53.5	-
Manufacture of wearing apparel	315	1.9	2.9	5.8	3.8	-	-	-
Manufacture of leather and related products	316	2.0	3.0	7.5	0.1	61.9	42.3	60.7
Wood product manufacturing	321	54.7	26.5	76.2	2.2	15.9	63.3	21.4
Furniture and related product manufacturing [1]	337	16.5	9.7	28.8	0.6	-	-	60.4
-Wood kitchen cabinet and countertop	*33711*	*8.9*	*5.1*	*11.9*	*0.2*	*65.5*	*58.2*	*50.1*
-Non-upholstered wood household furniture	*337122*	*1.5*	*1.5*	*4.5*	*0.1*	*20.1*	*49.9*	*42.0*
-Wood office furniture	*337211*	*1.5*					*80.8*	
-Custom architectural woodwork and millwork	*337212*	*4.7*	*3.4 C*	*10.2 C*	*0.2 C*	*73.9*	*33.2*	*66.9*
-Other	*-*	*0.0 A*	*0.0 A*	*0.0 A*	*0.0 A*	*-*	*-*	*-*
Ethyl alcohol manufacturing	325193	6.0					85.2	
Cyclic crude intermediate and gum and wood chemical manufacturing	325194	2.6	30.8	142.6	4.9	0.3	48.1	0.3
All other basic organic chemical manufacturing	325199	29.2					69.9	
Pharmaceutical and medicine	3254	84.5	53.4	78.9	0.3	-	10.6	-
-Medicinal and botanical	*325411*	*8.2*	*6.8*	*13.3*	*0.1*	*23.0*	*27.4*	*34.4*
-Pharmaceutical Preparation	*325412*	*59.6*	*24.6*	*42.4*	*0.2*	*-*	*-*	*-*
-In-Vitro Diagnostic Substance	*325413*	*11.9*	*2.3*	*4.2*	*0.0*	*-*	*-*	*-*
-Biological product (except diagnostic)	*325414*	*30.5*	*18.1*	*26.4*	*0.1*	*17.5*	*5.8*	*53.7*
-Other	*-*	*0.0 A*	*1.6*	*0.0 A*	*0.0*	*-*	*-*	*-*
Plastics and rubber products manufacturing [1]	326	5.4	3.3	10.3	0.2	-	-	-
TOTAL (Biomanufacturing - EU Based Definition)		**725.8**	**438.8**	**1363.8 P T**	**43.0 P T**			
TOTAL (Advanced Biomanufacturing - NAS Based Definition)		**140.7**	**94.6**	**259.9**	**6.4**			

Blue – Partially included for advanced biomanufacturing Red - These industries are excluded from advanced biomanufacturing
Environmental impact is measured based on EPA's TRACI measures

1. Introduction

1.1. Background

Many manufactured goods in the U.S. economy are produced using bio-based products and biotechnology; however, the bioeconomy is not tracked or broken out in U.S. economic data. Much of the economic data is broken out by North American Industry Classification System (NAICS) codes which are based on the type of product produced and not the methods used to produce the products. Therefore, biomanufactured items are often aggregated with other items that are produced using non-biotechnologies.

In addition to measuring the biomanufacturing economy, there is also a need to measure the economic costs and losses (e.g., lost batches) of the bioeconomy to identify common efficiency and productivity opportunities. Identifying areas of high economic impact, typically, requires an understanding of the costs/losses experienced by the industry of interest.

1.2. Scope

This report examines the U.S. biomanufacturing economy. As discussed in the report, there are generally two definitions of the bioeconomy. The first is found in the European Union and encompasses the production of biological resources and their conversion into products and energy. The second, found in the U.S., is much narrower and focuses on products that are driven by research and innovation. This report utilizes both of these definitions where, when applied to manufacturing, the former is referred to as "biomanufacturing" and the latter is a subset of biomanufacturing referred to as "advanced biomanufacturing."

This report examines industry data, including input-output data, to examine the size of the industry along with the assets, flow time, environmental impact, and supply chain components. When combined with other sources such as industry expertise, the findings can aid change agents, such as trade organizations and universities, in identifying potential efficiency and productivity improvements in the industry. This report goes on to examine opportunities for efficiency improvements in biomanufacturing.

1.3. Approach

Manufacturing includes investments in fixed assets along with a flow of costs, including materials, labor, and energy. This report relies on a number of different datasets on manufacturing and uses multiple methods to measure different aspects of the industry. Some portions of the biomanufacturing industry are estimated using findings from surveys of industry experts combined with industry data while other portions of advanced biomanufacturing are estimated using labor data. Some cost estimates are taken directly from industry data; however, supply chain costs are estimated using economic input-output analysis. Environmental impacts are estimated using environmentally extended input-output analysis and estimates of flow time were measured using methods developed in Thomas (2018a). Some opportunities for efficiency improvements are identified using investment analysis of data from onsite examinations of small and medium manufacturers.

Section 2 discusses the types of advancements that can make economic advancements for biomanufacturing and other technologies. Section 3 discusses evaluating and prioritizing public investments in efficiency and productivity to get the highest possible return. It discusses investment analysis and forecasting/predicting unknown data. Section 4 discusses the definitions of the bioeconomy and biomanufacturing in order to identify relevant economic activities. Section 5 estimates the value added for the biomanufacturing industry along with advanced manufacturing. Section 6 discusses assets and flow time for the industry while Section 7 discusses its supply chains and energy consumption. Section 8 examines efficiency improvement recommendations made to biomanufacturing industries by the Department of Energy (DOE) Industrial Assessment Centers (IAC). Finally, Section 9 discusses data gaps on biomanufacturing and Section 10 provides a summary of the report.

2. Types of Efficiency/Productivity Advancements in Biomanufacturing

Unfortunately, there are scarce and limited resources to invest in advancing biomanufacturing; therefore, to have the largest impact possible one must identify those advancements that have the highest returns. Additionally, there are also limited resources for identifying high return research. To have the highest return possible, change agents must use strategies that bias their efforts toward identifying high return research and use methods to sort and select the best of those projects. Additionally, the return on investments are not evenly distributed, with a small percent of the investments representing a large percent of the return. For instance, an analysis by Thomas (2022) shows that approximately 20 % of cost categories represent 82 % of the total potential savings (net present value) of 15 641 investments. A similar distribution exists for the internal rate of return for the same set of investments. Moreover, the potential savings is concentrated among a relatively smaller number of investments.

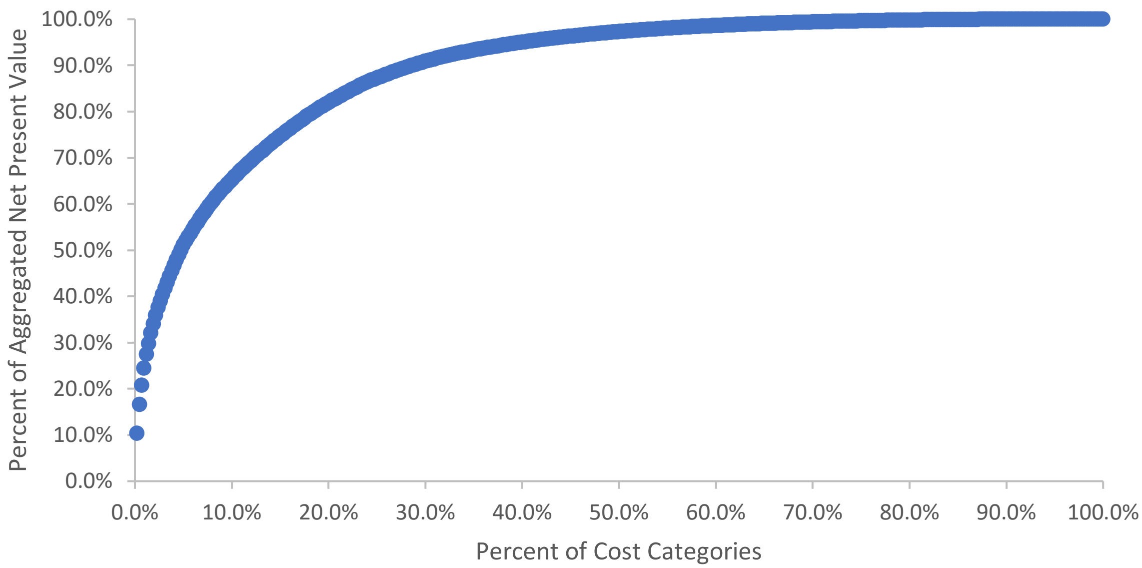


Figure 2.1: Cumulative Net Present Value by Percent of Cost Categories

This report identifies at least six categories of advancement or technology adoption (i.e., two advancement types with each having three different impact types), as listed in Table 2.1. There are advancements that include improvements to existing processes and those that significantly alter or create new processes. New processes typically require new materials, knowledge, and machinery, which may alter the supply chain. These changes can reduce costs, improve quality/performance, and/or reduce negative externalities. Some solutions might fit into multiple classifications. For example, energy efficient lighting fits into box 1A and 3A from Table 2.1. The classification in Table 2.1 is noted because identifying areas of high economic impact in each of these categories often requires different approaches. For instance, identifying a high return solution that improves existing processes might focus more on examining and classifying costs while advancements that create/use a new process might involve research and evaluations on new technologies, including insight from industry experts. The following sections discuss approaches to identifying areas of high economic return at the industry level for each of the categories in Table 2.1.

Table 2.1: Categories of Manufacturing Industry Improvements

		Type of Advancement	
		A	**B**
		Improves existing processes	**Alters or creates new processes**
1	**Reduces Cost**	Example: Use energy efficient lighting	Example: Automating production
2	**Improves Product Quality/Performance**	Example: Using sensors to detect defects	Example: Creating additive manufactured part that performs better than using traditional methods
3	**Reduces Negative Externalities (e.g., environmental impacts or safety hazards)**	Example: Use energy efficient lighting	Example: Adopting a new bioplastic that is easily recycled, but requires different machinery

Impact Type

2.1. Improve Existing Processes to Reduce Cost (Category 1A)

To identify areas of high economic impact that improves existing processes, it can be advantageous to classify, sort, and identify the highest costs within an industry. These industry costs can then be the first to be examined for possible efficiency/productivity improvements. There are at least two potential advantages to focusing on larger costs. The first advantage is that there is the potential for larger impacts. For instance, a $5 cost reduction has a maximum potential efficiency impact of $5 while a $100 cost reduction has a maximum impact of $100, a twenty-fold increase in potential. In addition to a higher maximum potential, larger costs require smaller percent reductions for the same dollar savings. For instance, to save $1 from a $1 cost, it requires a 100 % reduction. To save $1 from a $100 cost, it only requires a 1 % reduction in cost (see illustration in Figure 2.2), which may often be more attainable. It is frequently going to be easier to reduce a larger cost by 1 % than a smaller one by 100 %.

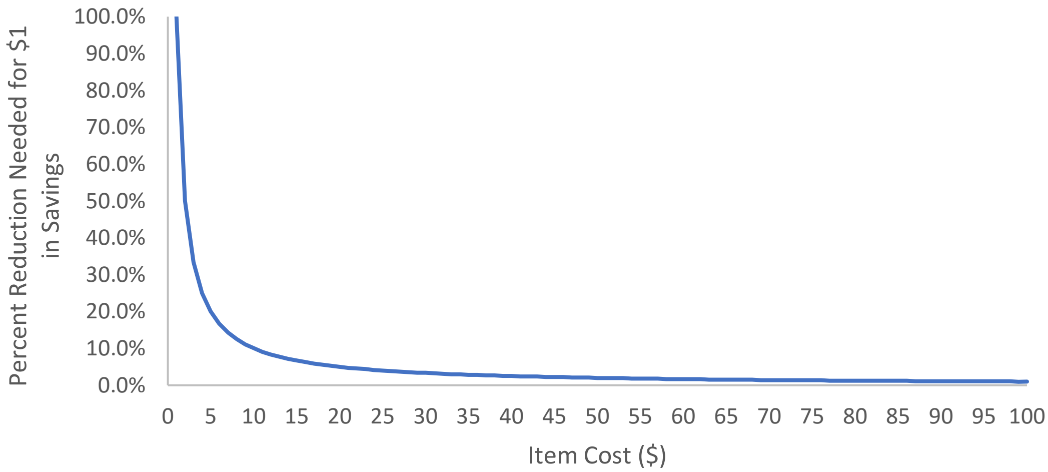
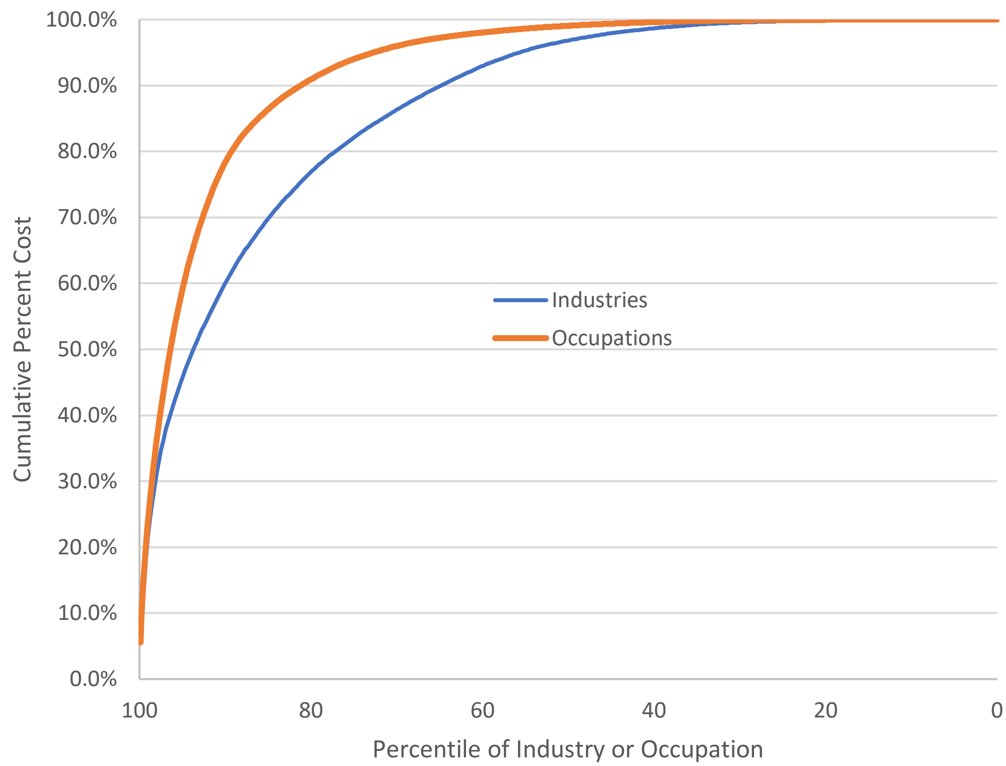


Figure 2.2: Percent Reduction Needed for a $1 savings, by Cost

Opportunely, costs are not evenly distributed. Typically, a small proportion of costs represent a large percent of the total. This follows a frequently invoked axiom that roughly 80 % of a problem is due to 20 % of the cause, a phenomenon referred to as the Pareto principle.[1] Manufacturing costs have a high tendency to follow this pattern. For instance, an examination of assembly-centric goods (see Figure 2.3) shows that approximately 20 % of the cost items (i.e., those above the 80th percentile) represent approximately 80 % of the total cost. These high-cost items have a higher potential cost reduction for an efficiency or productivity advancement. They also require a smaller percent reduction to have the same dollar impact. Another example of this distribution is found in research by Thomas and Kandaswamy (2019a), which examined supply chain value added in the U.S. for producing assembly-centric products (i.e., machinery, computers, electronics, and transportation equipment). An input–output model was used for the examination combined with other data. It determined that costs are disproportionally distributed such that 20 % of the cost items represent 80 % of the total cost.

[1] Hopp, Wallace J. & Mark L. Spearman. (2008) Factory Physics. Third Edition. Long Grove, IL: Waveland Press. (pp. 674).



Source: Thomas, Douglas. "Economic Guide for Identifying and Evaluating Industry Research Investments: A Focus on Applied Manufacturing Research." AMS 200-8. https://doi.org/10.6028/NIST.AMS.200-8

Figure 2.3: Line Graph of the Cumulative Percent of cost by Percentile of Industry/Occupation Cost (Assembly-Centric Products)

2.2. Improve Existing Processes and Increase Quality/Performance (Category 2A)

Similar to advancements in category 1A, the returns for advancements in category 2A are likely disproportionally distributed such that a small percent of the advancements account for a large percent of the total benefits. In the case of quality/performance of a product, these benefits are largely experienced by the user; although, the manufacturer can capture some of these benefits with higher prices or increased sales. Understanding the benefits means examining the costs and losses that the user experiences and how an increase in quality/performance of a product affects them. An example of this is found in Thomas et al. (2017), which examined the life-cycle cost of manufactured goods, focusing on passenger ground transportation. As shown in Table 2.2, this paper examined user costs associated with a product. These are the types of costs that are affected by quality/performance of a product. For instance, increased fuel efficiency decreases fuel costs for the user. Measuring these costs in detail can be a bit more complicated as they are not tracked in the same ways as industry costs. Additionally, some of these costs may be different units, as they might include personal time, health, or other non-financial items.

Table 2.2: Resources Related to Ground Passenger Transport, 2014

	$Billion 2014	Percent of Total Resources
Consumer purchases	**266.1**	**0.8%**
New motor vehicles	266.1	0.8%
Consumer maintenance, repair, and energy	**931.8**	**2.8%**
Public Transportation	99.8	0.3%
Motor vehicle parts and accessories	65.4	0.2%
Motor vehicle fuels, lubricants, and fluids	371.2	1.1%
Motor vehicle maintenance and repair	176.7	0.5%
Other motor vehicle services	77.6	0.2%
Consumer time usage for maintenance and repair (dollar equivalent)	141.1	0.4%
Vehicle maintenance and repair not done by self	28.2	0.1%
Vehicles	112.9	0.3%
Consumer transport time	**3329.6**	**10.2%**
Consumer time usage (dollar equivalent)	3329.6	10.2%
Travel (for work)	761.9	2.3%
Travel (other)	2567.8	7.8%
Commercial, industrial, and other maintenance, repair, and energy	**170.3**	**0.5%**
Gasoline**	170.3	0.5%
Commercial, industrial, and other purchases	**122.1**	**0.4%**
New motor vehicles	122.1	0.4%
Infrastructure	**76.9**	**0.2%**
Highways and streets	76.9	0.2%
Total - Resources related to discrete manufactured products	4896.8	14.9%
Total - annual resources (GDP and uncompensated labor time)	32771.5	100.0%

* Adjusted to 2014 using the Consumer Price Index for all consumers

** Assumes the ratio of new motor vehicle purchases to Motor vehicle fuels, lubricants, and fluids is the same for consumers as it is for commercial and industrial uses

Source: Thomas et al. (2017)

2.3. Reduce Environmental Impacts (Category 3A and 3B)

Three terms are popularly discussed regarding sustainability: circular economy, bioeconomy, and green economy. Each has a slightly different focus but often overlap. The circular economy emphasizes regenerative production-consumption systems (Amato and Korhenen 2021) and includes recycling, reuse, remanufacturing, repair, and product longevity among other things (Ekins et al. 2019). Descriptions of a circular flow of materials appears as early as the mid-1970's (Ekins et al. 2019). The bioeconomy tends to focus on utilizing biological resources for developing and producing goods and services while green economy tends to focus on renewable energy, although it also includes elements of reducing material and energy inputs, recycling, and reuse (Amato and Korhenen 2021). There are numerous publications that discuss and define circular economy, bioeconomy, and green economy that will not be reproduced here.

It is important to note that circular economy, bioeconomy, and green economy tend to refer to sets of solutions to the misalignment of incentives previously discussed. However, this is only partially true for bioeconomy, as it refers to the characteristics of a manufacturing process; thus, alignment only applies regarding environmental or sustainability issues. Despite language around these terms, they are not end goals by themselves, but rather a means for achieving a sustainable economy. At times these means can be in alignment with each other, but there are times when they offer competing objectives.

Although the terms circular economy, bioeconomy, and green economy are useful and commonly used, their definitions can be vague with many seeking to refine them. For instance, there are research papers that aim to understand the terms by systematically examining their usage (e.g., Homrich et al. 2018). The terms also often overlap each other. For instance, bioplastics are considered both green and circular, though they may not necessarily be either. There can also be tradeoffs between one another, and they are not always compatible with each other (Amato and Korhenen 2021). Thus, one solution might need to be selected over another. These challenges can make the terms limited in researching, developing, and identifying solutions to develop a sustainable economy. To develop the most sustainable economy possible, research and decisions must be based on their return on investment while fully capturing their impacts to sustainability.

The causes and potential solutions to an unsustainable economy are complex. The free market frequently works well for determining how resources should be allocated. However, there are barriers that prevent the free market from reaching an optimal solution in all situations. When this happens, it is typically called a market failure. Multiple market failures serve as a barrier to the adoption of a sustainable economy. Many of these amount to mismatches in incentives. Figure 2.4 maps the life cycle of a product and its materials and identifies some challenges to adopting a sustainable economy. One challenge is a mismatch in incentives between the producer and consumer. Producers have a limited ability to signal to consumers that their product performs better or lasts longer than their competitors' product (see #3 in Figure 2.4). Producers can offer warranties, guarantees, or build a brand reputation; however, warranties and guarantees can be misleading measures of quality. The difference between low life-expectancy and high life-expectancy products can be obscured with advertising, having a brand with a mix of low and high performing products, offering warranties with deductibles and prorated replacement offset by simply increasing the price of the product to cover the replacement of products that prematurely fail. Even when producers can differentiate their products, consumers often under value future savings (see #4 in Figure 2.4). This leaves little incentive for producers to design long lasting products that can be repaired and/or reused (see #1 in Figure 2.4).

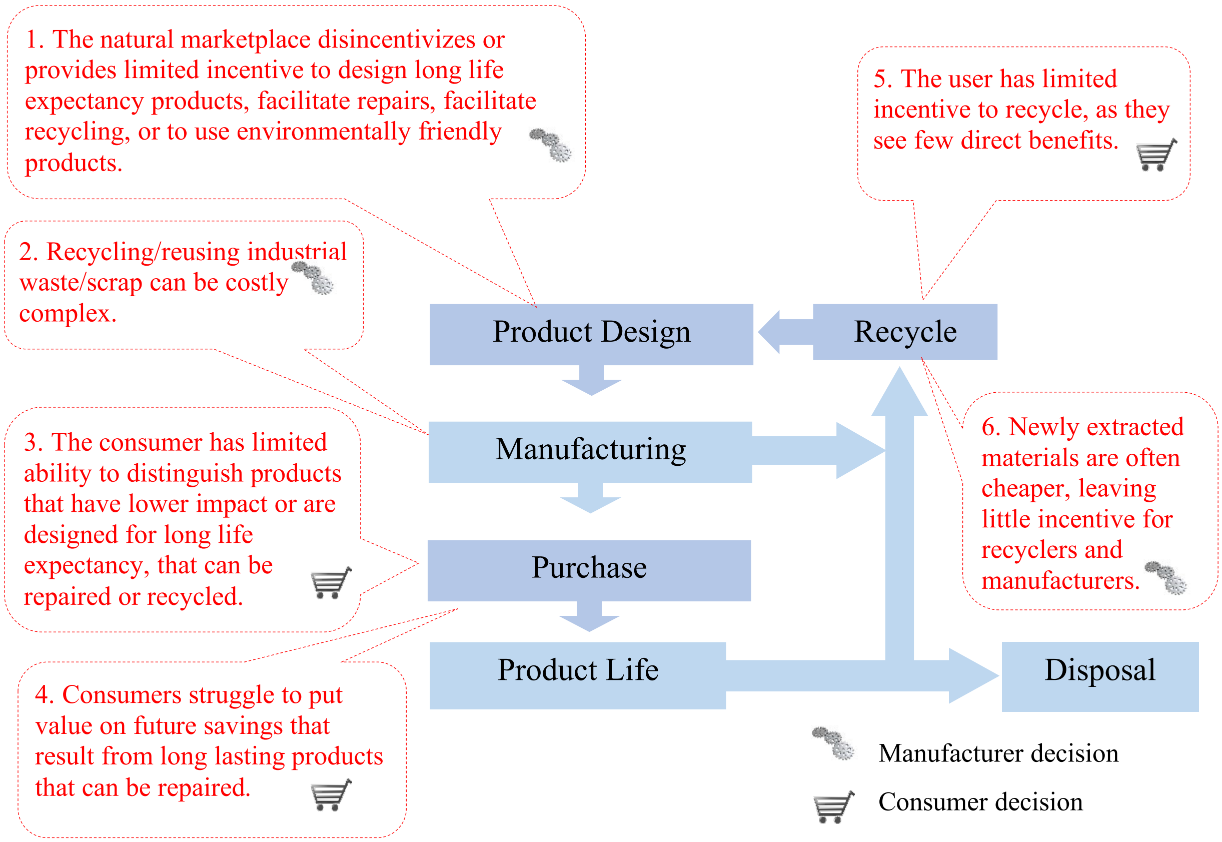


Figure 2.4: Economic Challenges to the Adoption of a Sustainable Economy that occur in a Free Market

Another challenge is a mismatch in incentives due to externalities where the manufacturer and consumer do not bear the full cost of producing and using a product, as the environmental impacts of a purchased product are experienced by people other than just the producer/consumer. This results in a lower than optimal incentive in designing products and processes to reduce environmental impact (see #1 in Figure 2.4). It also diminishes the incentive for consumers to recycle (see #5 in Figure 2.4) and for producers to purchase recycled material (see #2 and #6 in Figure 2.4), as they do not bear the full cost of newly extracted materials.

The challenges can be grouped into three primary incentive misalignments:

- **Design for longevity/reuse/repair/recycle and using materials/energy with a smaller footprint**: costs of design and production are borne by the manufacturer while benefits are experienced by society (i.e., reduced environmental impact).
    - **Complicating factor**: consumers struggle to distinguish products designed for longevity/reuse/repair or ones that use environmentally friendly materials/energy
    - **Complicating factor**: consumers struggle to value future savings/benefits
    - **Complicating factor**: in addition to the costs of design, manufacturers can experience diminished sales when products last longer

- **Complicating factor**: in addition to the costs of design, reusing materials can be costly and complex with many challenges
- **Complicating factor**: Longer lasting products may not be used to their full capacity

- **Recycling**: The user and manufacturer bear some costs of recycling (e.g., separating, transporting, and fees) while the benefits are experienced by society as a whole
    - **Complicating factor**: societal benefits are not always obvious (e.g., observable) to society
    - **Complicating factor:** domestic and international taxes, subsidies, and regulations related to fossil fuels or recycling can affect the economics of recycling
- **Decreasing waste, energy use, and material use**: Producers and consumers bear the cost of purchasing or using methods/items that decrease waste, energy, and material use while society experiences the benefits
    - **Complicating factor**: It isn't always clear what method or product results in decreasing waste, energy use, and/or material use

These misalignments result in a system failure. That is, the current system of exchange does not address these problems. Even if a manufacturer wants to participate in sustainable development, market pressure can significantly diminish their ability to do so. This pressure could even drive businesses that engage in sustainable practices out of business, leaving only those firms that do not invest in sustainability because they do not have to bear the extra cost. Consumer preferences can pressure firms to increase sustainability; however, without any reliable means for discerning sustainable performance, it may only result in the appearance of sustainability. Moreover, the unsustainable economy is typically a result of logical and rational decisions made by individuals and firms from their stakeholder perspective.

There are several potential solutions to mitigate the challenges to a sustainable economy. Kirchherr et al. (2017) presents a summary of solutions; however, they present them as barriers to a circular economy (i.e., lack of solutions). The four categories of solutions include the following: Cultural, Technological, Market, and Regulatory. For this report, we will use an altered version of this list for categorizing solution types that create a sustainable economy:

- **Cultural solutions**: putting ethical or moral pressure on companies and/or individuals to adopt practices related to a sustainable economy
- **Information dissemination**: educating companies and/or individuals on issues related to a sustainable economy
- **Technological solutions**: developing new technologies or adopting existing technologies that facilitate a sustainable economy
- **Standards**: developing standards that facilitate the adoption of practices related to a sustainable economy
- **Legislation**: Mandating practices related to a sustainable economy and/or implementing taxes, subsidies, or other policy-based incentives for adoption of such practices

The solutions either aim to reduce the effect of the misalignment (e.g., reduce costs, increase incentives, or reduce the negative outcomes directly) or realign the incentives for a sustainable economy so that the logical and rational outcome for the individual or company matches that of society. Cultural solutions, for instance, could create an additional cost in the form of guilt or boycotts if one does not participate in a practice related to the sustainable economy. Note that this report focuses on technological solutions and standards.

The list above differs from Kirchherr et al. (2017) in that it does not have a “Market” category. This was removed as all these items affect the market, and our barrier list describes market conditions. The list above also includes two additional categories: “Information dissemination” and “Standards.” “Information dissemination” could be considered a component within other categories. It is highlighted here as it is often overlooked. Misperceptions are common and can become significant barriers to progress in addressing societal issues. “Standards” could have been considered part of the “Technological Solutions;” however, it is not a perfect fit because it is focused on consistency instead of innovation of technologies. The list above also changes the “Regulations” category from Kirchherr et al. (2017) to “Legislation” to include taxes, purchasing and access requirements, and subsidies, as some might not see these as regulations.

The solutions listed above work through a number of means, including

- Increasing longevity of products
- Producing energy using environmentally friendly technology
- Recycling
- Reducing material and energy use
- Reusing/repairing products
- Using products/materials with a smaller impact

Individual solutions can be categorized by solution type, the means by which they achieve sustainability, and their primary effect on the misalignment of incentives (i.e., increase costs of unsustainable activities, decrease the cost of sustainable activities, realignment of incentives, or mitigate negative externalities), as illustrated in Table 2.3. For instance, consider a standard that develops a metric measuring the expected life of a product. This would allow consumers to

Table 2.3: Intended Primary Effect of Public/Industry Level Research Investments by Solution Type and Means for Achieving Sustainability

		Means for Achieving Sustainability					
		Increase product longevity	Produce cleaner energy	Recycle	Reduce material and energy use	Reuse/repair products	Use low impact products/materials
Solution Type	Cultural solutions	$	$	$	$	$	$
	Information dissemination	-$, Θ	-$	-$	-$	-$, Θ	-$
	Technological solutions	-$	-$	-$	-$	-$	-$
	Standards	-$, Θ	-$	-$	-$	-$, Θ	-$
	Regulations, taxes, and subsidies	-$, $, Θ, ֍	-$, $, Θ, ֍	-$, $, Θ, ֍	-$, $, Θ, ֍	-$, $, Θ, ֍	-$, $, Θ, ֍

Primary Effect on the Misalignment of Incentives

$ Increase the costs of unsustainable activities

-$ Decrease the cost of sustainable activities

Θ Realignment of incentives

֍ Mitigate negative externalities

reliably predict and compare product life-expectancies so that, if they want, they can choose longer lasting products. This would fall under the “Standards” row and “Increase Product Longevity” column. In terms of sustainability, this standard realigns incentives, which is represented with the symbol Θ. Another example might be a material standard for plastics that standardizes plastic additives. This might increase the cost of producing some products; however, it would decrease the cost of recycling through economies of scale (i.e., decrease the cost of sustainable activities, which is represented with -$), as more plastics could be recycled together. That is, if a firm decides to increase their sustainability by using materials that can and will be recycled, the true cost of doing so is decreased as a result of the standard. Otherwise, the firm might, for instance, have to invest in developing recycling facilities specific to their material. This standard would fall under the “Recycle” column and “Standards” row, as it is a standard that facilitates recycling.

When estimating the return for an investment in sustainability, it is important to consider the probability of success. An investment analysis is a forecast or prediction of the results of one’s decisions. Like any model, this forecast has assumptions and uncertainties. Investments in sustainability can have a significant amount of uncertainty. For instance, there is uncertainty for how society might respond to public service announcements or how manufacturers might respond to new regulations, costs, or standards. Moreover, it is important to incorporate these uncertainties when evaluating the return for an investment. Society level sustainability typically includes changing the behavior of multiple people; thus, two primary factors for success are the number of people that need to change their behavior and the magnitude of the behavior change. High numbers of people are more difficult to reach and as the number of people being asked to change increases, there is an increase in the number of people who might create barriers. Changing patterns of behavior can be difficult even if a person wants to change. The more change that is being asked of them, the more difficult it will be to implement. A third factor is how the change relates to incentives for the person/organization being asked to change. The more a change is inconsistent with individual incentives, the more difficult it will be to implement. Thus, the success of a sustainability solution increases as the number of people needed to change decreases, the magnitude of change decreases, and the incentives increase, as illustrated in Figure 2.5.

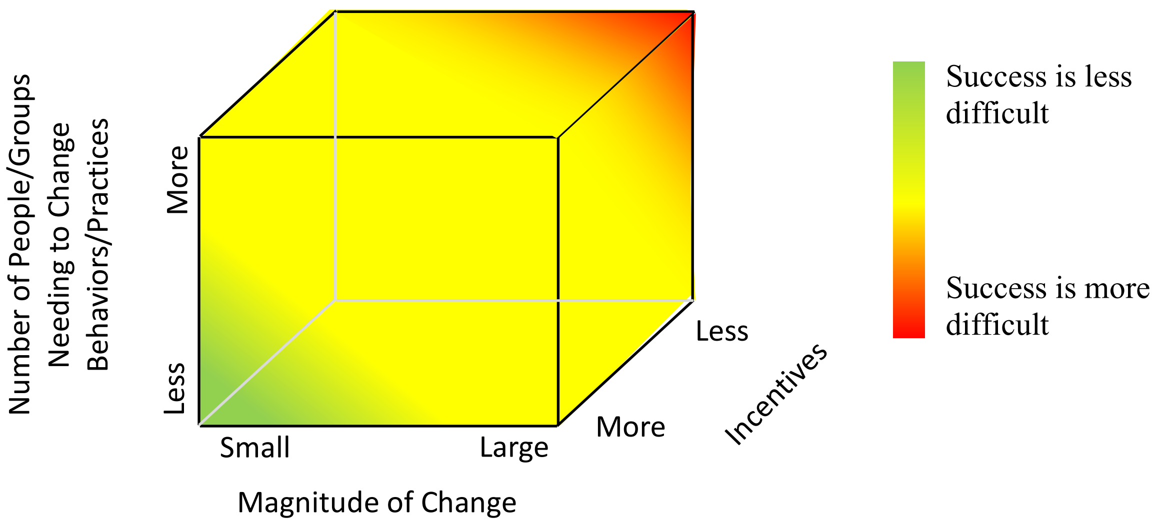


Figure 2.5: Additional Challenges, besides Cost, to Creating a Sustainable Economy

One means for achieving a higher return is to make investments that achieve more than one goal, such as decreasing costs and environmental impacts. A paper by Thomas (2018b) examined the life-cycle cost of passenger ground transportation as a proof of concept in identifying both high cost and high environmental impact areas of manufacturing. Public research that focuses on these items might be more economical than other areas. U.S. input-output analysis along with a number of datasets are used to examine the supply chain for production and use of ground transportation equipment. Another paper by Thomas et al (2017) conducted a similar analysis identifying economy-wide opportunities for efficiency improvement in manufacturing.

2.4. Significantly Altering or Creating New Processes to Reduce Cost and/or Improve Quality/Performance (Category 1B and 2B)

An example of an advancement that results in a new process that improves quality/performance is additive manufacturing. It is a technology that is very different from traditional methods of manufacturing products. Current research on additive manufacturing costs reveals that this technology is cost effective for manufacturing small batches and, possibly, with increased automation distributed production may be cost effective for some items. This technology is frequently useful for unique or customized parts. It also allows for the manufacture of products that might not have been possible using traditional methods. They may have new abilities, extended useful life, or reduce the time, labor, or natural resources needed to use these products. For example, automobiles might be made lighter, reducing fuel costs or combustion engines might be designed to reduce cooling needs. Because this is a newer technology, costs can change more rapidly and the research on costs is still developing. This makes it difficult for change agents to examine the costs/benefits of this technology or others, such as many biomanufactured goods. Identifying these types of advancements requires expert insight, but still requires economic evaluations. For instance, experts can identify the types of products and situations where additive manufacturing is cost effective.

3. Economic Evaluation of Industry Advancements

Frequently, identifying high return public research investments requires making forecasts and investment decisions with incomplete and imperfect information. Consequently, these forecasts have greater uncertainty and might even be considered back-of-the envelope estimates. Despite these shortcomings, it has been shown that some methods for making forecasts have greater accuracy than others. The Intelligence Advanced Research Projects Activity (IARPA), part of the Office of the Director of National Intelligence, set out to improve American intelligence, which often includes making forecasts such as estimating the probability of an Israeli strike on Iranian nuclear facilities. To determine and improve the performance of their intelligence forecasts they created a forecasting tournament (Tetlock and Gardner 2015). This competition created a great deal of information on what works and how well. In conclusion, some methods are far more accurate than others, even to the point of outperforming professional intelligence analysts with access to classified information (Tetlock and Gardner 2015). Unfortunately, many do not use these methods often due to biases and overconfidence in one's own knowledge.

There is a temptation or even a tendency for decision makers to use their instinct or intuition to determine which projects to invest. To some extent this should be resisted, as humans are vulnerable to being heavily influenced by immaterial feelings and emotions (Kahneman 2011; Areily 2008). For instance, a project might seem more appealing to a decision maker because they are better friends with the researcher, or they contributed to the idea. Research has shown that even having heard uninformative numbers can influence our judgement (Wilson et al. 1996). Many economic researchers have investigated these phenomena, including Daniel Kahneman, a Nobel Prize winner in economics. Despite one's best efforts, it has been shown that humans are not able to completely separate emotions from logical decision making (Kahneman 2011; Ariely 2008). The influence is nearly inescapable.

When intuition is broad and fuzzy it is more vulnerable to being based on unsound reasoning. *If it is necessary to use intuition, it should be on the evaluation of specific factors of an investment*. For instance, if a particular cost of an investment is unknown, one might use individual insight to surmise the value of this cost rather than using intuition to evaluate the entirety of the project and whether it warrants investment. Below is a description of a basic method for investment analysis for industry advancements followed by a discussion about forecasting, which is frequently necessary for conducting an investment analysis.

3.1. Investment Analysis

Given that there are limited resources for investment, to produce the most sustainable economy possible it is necessary to identify those solutions that have the largest return on investment for sustainability. Thomas (2017) presents a guide for investment analysis, which discusses net present value, internal rate of return, and uncertainty analysis among other items. These methods can be used along with methods for examining environmental impact to identify solutions that have the highest return. For instance, some environmental impacts can be converted to carbon equivalents and then to dollar values using an estimate for the cost of carbon (EPA 2016). This report will utilize a slightly altered approach where the benefits remain in units of environmental impact with different impact types weighted using the Analytical Hierarchy Process (see

Appendix B), as calculated in NIST's Manufacturing Cost Guide (Thomas 2019a). These methods are not from the natural sciences but drawn from the decision sciences.

A benefit-cost ratio can be used to identify high-return investments. A graphical representation like that from Thomas and Kandaswamy (2019b) can give a visual aid for identifying relative returns (see Figure 3.1). The projects in the figure are drawn as boxes to represent a range of costs and benefits. The benefit cost ratio for projects can be visually examined by drawing a line from the origin through the top left corner of the projects graph and another through the bottom right corner, as illustrated for Project A in Figure 3.1. Because the slope of the line represents a constant benefit cost ratio at the intersecting point of the project, any projects, or portions thereof, that lie above and to the left of the upper line outranks the project (i.e., Project E and Project B outrank Project A). Any projects that lie below and to the right of the lower line are outranked (i.e., Project A outranks Project D). Projects that lie between the upper and lower lines have overlapping benefit cost ratios with Project A.

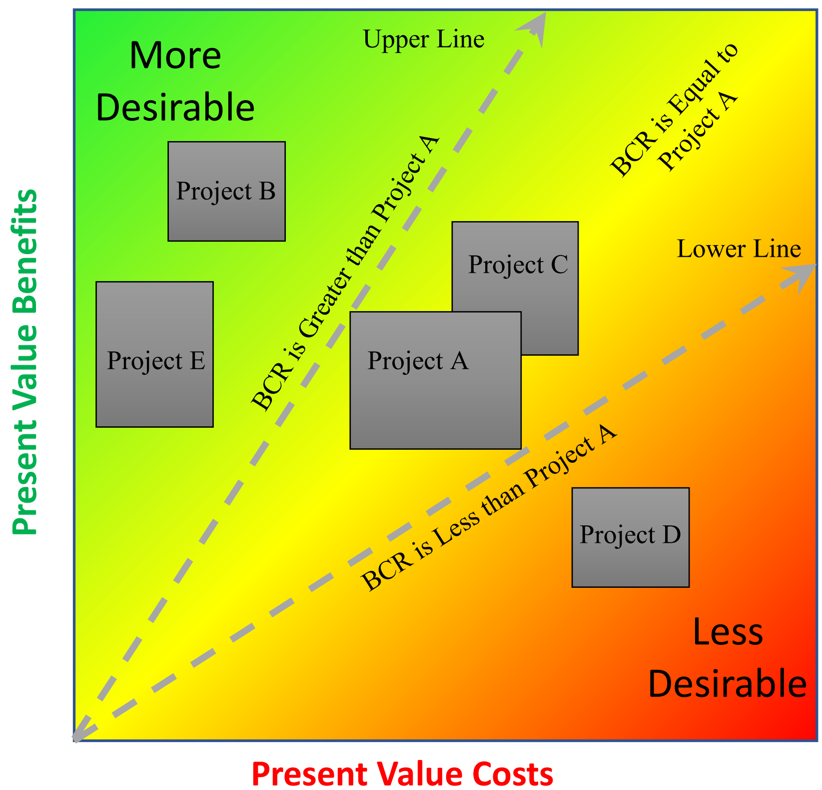


Figure 3.1: Graphing Costs and Benefits and the Benefit-Cost Ratio (BCR)

3.2. Forecasting

When conducting an investment analysis of a potential public investment, there are frequently many unknown values. These values need to be forecasted or predicted for an analysis to be completed. In the literature on forecasting, some common themes arise. Below is a discussion on some more important points.

Clarify and Refine the Problem/Question: It is important to ensure that relevant questions are being asked. Frequently, pursuits of information can be sidetracked by topics that are only adjacent to the true concerns at hand. The purpose of the forecasts discussed here are to identify the highest performing public investments, given the constraints and resources available. For instance, the belief of how important a technological advancement is might be irrelevant as to the scale of its economic impact compared to other public investments, as it may or may not actually translate into large returns, may only apply to a small number of firms, may not be viable, or it requires overwhelming sums of investment. Identifying high performing investments requires forecasting the costs and benefits of a particular investment as it compares to other investments.

Extraneous Information and Overweighting: When forecasting, it is important not to overweight particular types of information (Tetlock and Gardner 2015). Sometimes too much can be read into a piece of evidence. For instance, a piece of evidence may only suggest something is possible rather than it being probable.

Overconfidence: A common challenge that is faced when forecasting is overestimating one's own knowledge and abilities (Van den Steen 2004). For instance, in a survey of 161 students, 93 % estimated that they were above the median in driving ability (Svenson 1981); however, it is not possible for 93 % of drivers to be above the median . One might weigh their own evaluations/methods more than others simply because it is their method/idea.

Create Manageable Sub-Problems: The values to be forecasted can be broken up into manageable sub-problems to get a more accurate estimate (Tetlock and Gardner 2015). To illustrate, consider a survey that asks someone to estimate the hours per year they spend driving their car compared to one that asks each component of their drive time (e.g., number of hours per day they spend driving to and from work). An aggregated question such as one on the total hours per year they spend driving is difficult to answer, as they must consider all at once the different places that they drive. Someone is much more likely to estimate with accuracy the amount of time they spend driving to work and other individual components of their total driving. To the extent possible, break large problems into smaller sub-problems, utilize known values, and utilize comparisons to other similar circumstances.

Expert Opinion: In some situations, expert opinion can be quite useful; however, there are some limitations that are often overlooked. Expert opinion provides increased accuracy in a forecast when the opinion is within their expertise; thus, it is important to identify the boundaries of one's knowledge (Burgman et al. 2011). For instance, a physicist can provide a great deal of expertise in physics, but that may not translate into understanding the economic and social benefits that result from advancements in physics, as this is a social science question. Additionally, experts can perform poorly when there is limited feedback (Burgman et al. 2011); that is, when their predictions are rarely confirmed/refuted.

Testable Predictions: Forecast accuracy is improved in the presence of feedback. That is, when predictions can be confirmed/refuted. This also implies that forecasts need to be testable or confirmable. For instance, identifying that benefits of a particular public investment are "large" or "important" is not a testable prediction, as these terms are not clearly defined. That is, at no point in the future can it be refuted or confirmed when compared to the actual events/outcomes that transpire. On the other hand, a forecast that estimates a range of dollar savings from a public investment is a testable prediction. At some point in the future, researchers could collect data, make estimates of savings, and compare it to the prediction.

Accuracy in Numbers: It is well established that forecast accuracy is increased by including more people's input into the forecast (Tetlock and Gardner 2015). Therefore, it is beneficial to have a team of people or to survey individuals in order to estimate and answer manageable sub-problems.

4. Defining and Identifying Biomanufacturing

There are a number of definitions applicable to biomanufacturing. This report will focus on two general definitions for biomanufacturing that can be used to define what industries are included. The first definition is that found in the European Union:

> "The bioeconomy encompasses the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. It includes agriculture, forestry, fisheries, food, and pulp and paper production, as well as parts of the chemical, biotechnological, and energy industries. Its sectors have a strong innovation potential due to their use of a wide range of sciences (life sciences, agronomy, ecology, food science, and social sciences), enabling and industrial technologies (biotechnology, nanotechnology, information and communication technologies, and engineering), and local and tacit knowledge (Connelly 2020)."

For manufacturing, EU measures of the bioeconomy generally include food manufacturing, beverage manufacturing, tobacco manufacturing, portions of textile manufacturing, portions of apparel manufacturing, leather and related products, wood products, paper products, portions of chemical manufacturing, portions of pharmaceutical manufacturing, portions of rubber and plastic manufacturing, and portions of furniture manufacturing among some other nonmanufactured items. This is broader than definitions found in the U.S. such as the following:

> "A bioeconomy is one based on the use of research and innovation in the biological sciences to create economic activity and public benefit" (U.S. OSTP 2012).

> "The bioeconomy represents the infrastructure, innovation, products, technology, and data derived from biologically-related processes and science that drive economic growth, improve public health, agricultural, and security benefits" (U.S. OSTP 2019).

> "The U.S. bioeconomy is economic activity that is driven by research and innovation in the life sciences and biotechnology, and that is enabled by technological advances in engineering and in computing and information sciences" (Connelly et al 2020).

The narrower definitions found in the U.S. excludes tobacco manufacturing, leather products, wood manufacturing, paper products, furniture manufacturing, and apparel among some other nonmanufactured items (Congressional Research Service 2021). However, the NIST Bioeconomy Lexicon provides a broader U.S. definition for the bioeconomy and more specifically biomanufacturing:

> Bioeconomy: "economic activity derived from the life sciences, particularly in the areas of biotechnology and biomanufacturing, including industries, products, services, and the workforce" (NIST 2022).

> Biomanufacturing: "the use of biological systems to produce goods and services at commercial scale." (NIST 2022)

For this report, both the broad and narrow definitions are utilized. For manufacturing, the broader EU definition and that from the NIST Bioeconomy Lexicon is referred to as biomanufacturing while the other narrower definitions found in the U.S. is referred to as advanced biomanufacturing. Additionally, when measuring direct value added, this report examines the industries that produce goods using biomanufacturing processes; thus, those that produce items adjacent to this industry, for instance those that produce equipment for biomanufacturing, are excluded from direct value added. These items are implicitly included in the estimates for indirect (e.g., supply chain) value added. For this report, a product is only considered a biomanufactured product if the finished product's primary material value is derived from biomaterials. Additionally, advanced biomanufacturing primarily includes, but is not strictly limited to, those activities that grow biological molecules and materials along with those economic activities that alter biological material using highly specialized equipment often through non-mechanical means.

4.1. Standard Categorization of Economic Activity

Domestic U.S. economic data tends to be classified using NAICS codes. It is the standard used by Federal statistical agencies classifying business establishments in the U.S. NAICS was jointly developed by the U.S. Economic Classification Policy Committee, Statistics Canada, and Mexico's Instituto Nacional de Estadística y Geografía and was adopted in 1997.[2] NAICS has several major categories each with subcategories. Historic data and some organizations continue to use the predecessor of NAICS, which is the Standard Industrial Classification system (SIC). NAICS codes are categorized at varying levels of detail. Table 4.1 presents the lowest level of detail, which is the two-digit NAICS. There are 20 categories. Greater detail is provided by using additional digits; thus, three digits provides more detail than the two digit and the four digit provides more detail than the three-digit. The maximum is six digits, as illustrated for automobile manufacturing (NAICS 336111) and light truck and utility manufacturing (NAICS 336112). Sometimes a two, three, four, or five-digit code is followed by zeros, which do not represent categories. They are null or place holders. For example, the code 336000 represents NAICS 336. The results presented in the Manufacturing Cost Guide have varying levels of NAICS due to data availability. This classification system is very useful and can be used to identify some biomanufacturing industries; however, since it is based on product categories rather than production processes, it can be difficult to identify some biomanufactured goods. A particular product type (e.g., plastic) can be made with both biological and non-biological processes.

One means for identifying and measuring biomanufacturing activities is by using occupational data. U.S. federal statistical agencies classify workers into occupational categories for collecting and distributing data on employees. The 2010 version has 840 occupations, which are categorized into 23 major groups. Similar to the NAICS codes, additional digits represent greater detail up to a maximum of six digits, as illustrated for SOC 514011 and SOC 514012 in Table 4.2, which presents the 23 major groups. The SOC classifies all occupations in which work is performed for pay or profit. It was first published in 1980. It was revised in 2000 and then again revised in 2010. The Bureau of Labor Statistics now publishes occupation data based on this system.

[2] U.S. Census Bureau. North American Industry Classification System. <http://www.census.gov/eos/www/naics/>

4.2. Food and Beverage Manufacturing

Food and beverage manufacturing are categorized as NAICS 311000 and 312000. It includes, but is not limited to, canning, fermentation, freezing, pasteurization, smoking, grinding, milling, adding salt/sugar/fats to, and/or heating biological material for consumption. For this report, advanced biomanufactured food and beverage includes growing material and altering biological material primarily through non-mechanical means using specialized equipment (e.g., fermentation).

Table 4.1: North American Industry Classification System, Two Digit Codes with Example Breakout for Automobile Manufacturing

Sector	Description
11	Agriculture, Forestry, Fishing and Hunting
21	Mining, Quarrying, and Oil and Gas Extraction
22	Utilities
23	Construction
31-33	Manufacturing
336	*Transportation Equipment Manufacturing*
3361	*Motor Vehicle Manufacturing*
33611	*Automobile and Light Duty Motor Vehicle Manufacturing*
336111	*Automobile Manufacturing*
336112	*Light Truck and Utility Manufacturing*
42	Wholesale Trade
44-45	Retail Trade
48-49	Transportation and Warehousing
51	Information
52	Finance and Insurance
53	Real Estate and Rental and Leasing
54	Professional, Scientific, and Technical Services
55	Management of Companies and Enterprises
56	Administrative and Support and Waste Management and Remediation Services
61	Educational Services
62	Health Care and Social Assistance
71	Arts, Entertainment, and Recreation
72	Accommodation and Food Services
81	Other Services (except Public Administration)
92	Public Administration

4.3. Biomanufactured Pharmaceuticals and Medicine

Biomanufactured pharmaceuticals and medicines are captured in portions of NAICS 3254. Based on an interview with a former pharmaceutical employee, three major forms of pharmaceuticals include dry product, sterile injectables, and fluids. The first step in the production of these products is in producing and/or mixing the chemical/biological materials, also called the active pharmaceutical ingredients (API). Biopharmaceutical API's are produced in a series of steps (Jozala et al., 2016):

- Fermentation in a bioreactor to create API's
- Harvest the cells from fermented material
- Separate the needed material using chromatography
- Purification/polishing of the material
- Checking for quality control

Biomanufactured medicines also include grading, grinding, and milling of uncompounded botanicals.

Table 4.2: Standard Occupational Classification System, Two Digit Codes with Example Breakout for Machine Tool Operators

Occupation Code	Occupation Name
11	Management Occupations
13	Business and Financial Operations Occupations
15	Computer and Mathematical Occupations
17	Architecture and Engineering Occupations
19	Life, Physical, and Social Science Occupations
21	Community and Social Service Occupations
23	Legal Occupations
25	Education, Training, and Library Occupations
27	Arts, Design, Entertainment, Sports, and Media Occupations
29	Healthcare Practitioners and Technical Occupations
31	Healthcare Support Occupations
33	Protective Service Occupations
35	Food Preparation and Serving Related Occupations
37	Building and Grounds Cleaning and Maintenance Occupations
39	Personal Care and Service Occupations
41	Sales and Related Occupations
43	Office and Administrative Support Occupations
45	Farming, Fishing, and Forestry Occupations
47	Construction and Extraction Occupations
49	Installation, Maintenance, and Repair Occupations
51	Production Occupations
514	*Metal Workers and Plastic Workers*
5140	*Metal Workers and Plastic Workers*
51401	*Computer Control Programmers and Operators*
514011	*Computer-Controlled Machine Tool Operators, Metal and Plastic*
514012	*Computer Numerically Controlled Machine Tool Programmers, Metal and Plastic*
53	Transportation and Material Moving Occupations
55	Military Specific Occupations

4.4. Bioplastics

Bioplastics are produced from natural resources such as vegetable oil or starch. There is not a specific NAICS code for bioplastics; however, it would be included in *NAICS 326 - Plastics and Rubber Products Manufacturing*. As discussed later, bioplastics are a relatively small percent of all plastics and are, typically, made of sugarcane or corn. Some bioplastics are biodegradable while others are not (Ashter 2016). PLA bioplastic is, for example, made primarily by taking corn and mixing with Sulphur dioxide and hot water to breakdown the corn (Cho 2017). It is then mixed with additional ingredients. PHA bioplastic is, typically, made from microorganisms that make plastic from biomaterials.

4.5. Biofuels and Biochemicals

Two major biofuels include ethanol and biodiesel. Ethanol (also known as ethyl alcohol) is produced for multiple purposes, including for human consumption. Biodiesel is produced as a reaction between alcohol, typically methanol produced from natural gas, and oil (Clean Fuels Alliance 2012). There is about 2.5 gallons of methanol for every 10 gallons of oil (Koff 2014). Note that ethanol has its own code, *NAICS 325193* while biodiesel is listed in three NAICS codes:

- 324110 Biodiesel fuels made in petroleum refineries
- 324199 Biodiesel fuels not made in petroleum refineries and blended with purchased refined petroleum
- 325199 Biodiesel fuels not made in petroleum refineries and not blended with petroleum

For this report, only biodiesel listed in 325199 is included as biomanufacturing, as both of the other NAICS codes include petroleum blended with natural oils and would likely be considered a biodiesel blend. The most common type of biodiesel blend is B20, which is 6 % to 20 % biodiesel blended with petroleum diesel (U.S. Department of Energy 2013). Note that the natural oils produced for these NAICS codes along with the biodiesel produced for the purpose of blending would still be included in this report's estimate of biomanufacturing. Including the petroleum-based biodiesels becomes problematic, as it becomes difficult to draw the boundaries on what is and is not biomanufactured. For instance, ethanol is added to gasoline; thus, one might argue that gasoline is a biomanufactured product. Another instance of question might be found in an automobile that contains a bioplastic component – is the entire car now part of the bioeconomy. For this report, a product is only considered a biomanufactured product if the finished product's primary material value is derived from biomaterials. Note that a number of other biochemicals are also included in 325199, such as chloroform, citronellal, and sorbitol among many others.

4.6. Furniture, Paper, Tobacco, Textiles, Apparel, Leather, and Wood Products

The last category of biomanufacturing includes activities that are predominantly mechanical operations; although, there are some non-mechanical processes. These categories include the production of tobacco (NAICS 3122), textiles (NAICS 313 and 314), apparel (NAICS 315), leather (NAICS 316), wood products (NAICS 321), paper (NAICS 322), and furniture (NAICS 337).

5. Estimating the Biomanufactured Economy

There are several challenges and caveats in measuring the biomanufactured economy, including selecting a metric (e.g., value added or shipments) and the extent that supply chains are included. The following sections discuss these issues and provides an estimation of the biomanufacturing economy.

5.1. Economic Metrics: Shipments and Value Added

Shipments, which is sometimes referred to as output, is the net selling value of all products shipped. This value is an easier number to estimate, but it can result in double counting the costs of producing a product. For instance, in Figure 5.1, industry A contains three establishments[3] where establishment X ships items to Y who ships items to Z. Thus, the products of establishment Z contain products of establishment X and Y with the value of shipments reflecting the value of all three establishments. The products of establishment Y contain the products of establishment X. When data is collected to calculate shipments, the value from all three establishments are added together. This means that the value of shipments at X are counted 3 times: 1) when X reports shipments, 2) the value of X's shipments embedded in Y's shipments, and 3) the value of X's shipments embedded in Z's shipments (i.e., the resale of X's share of the shipments). Caution should be exercised when using "purchases by industry," as this is equivalent to shipments and double counting can occur when adding data together. Double counting is not present in value added, which can also be referred to as gross domestic product (GDP), as this is calculated by taking the value of shipments and subtracting the purchases of goods/services from other establishments (Dornbusch

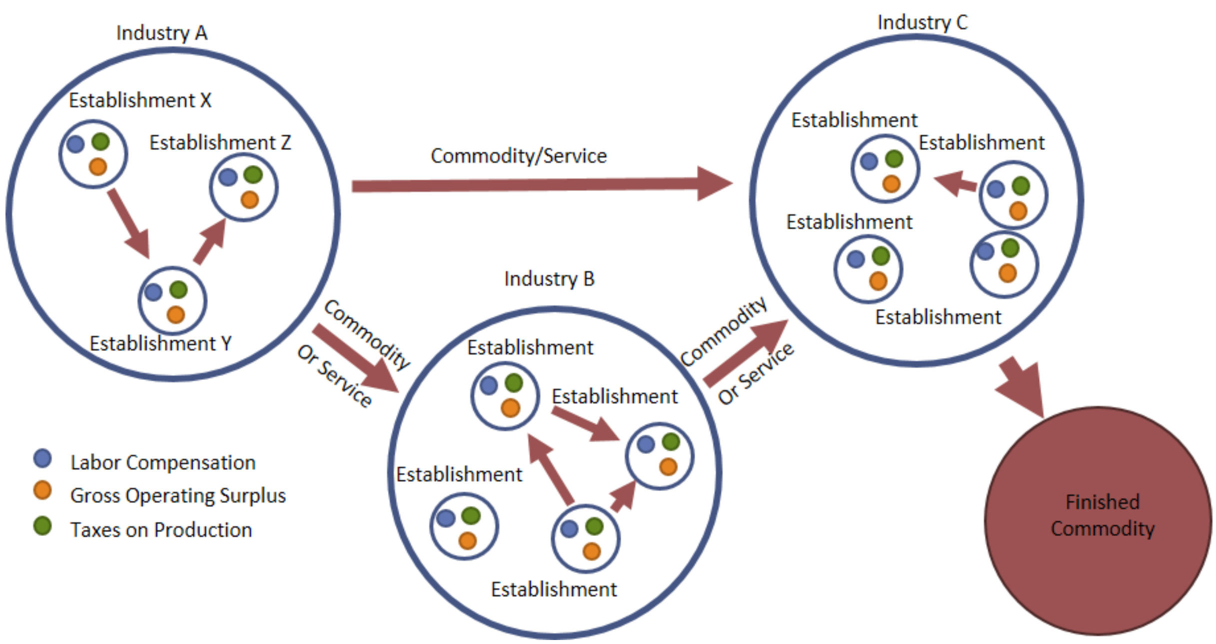


Figure 5.1: Supply Chain Illustration

[3] Note that an establishment is a physical location of economic activity such as a factory. It should not be confused with a company or enterprise. Each establishment (e.g., factory) is categorized by NAICS code. A company could have multiple establishments categorized into different NAICS codes.

2000). The remaining value contains labor compensation, gross operating surplus (which includes profit), and taxes on production. The downside of using value added is that it breaks all products into their subcomponents and services. Thus, if one wants to know about the manufacturing industry's electricity costs using value added, they would have to sum the value added from the "Electric power generation" industry (NAICS 221100) along with all the value added that the "Electric power generation" industry used to produce electricity, such as coal, natural gas, and transportation.

5.2. Biomanufacturing Shipments, Value Added, Indirect Value Added, and Environmental Impact

This report relies on two datasets to estimate value added and indirect value added: Annual Survey of Manufactures (ASM) and NIST's Manufacturing Cost Guide, which is derived from a number of datasets. Although it is an imperfect metric, shipments are estimated as well, as it is occasionally cited in some publications. Using these datasets allows us to create value added estimates that are consistent with those used to estimate U.S. GDP. The two datasets used each have their own advantages and disadvantages. The advantage of the Annual Survey of Manufactures data is that it is primarily based on recently collected data. Therefore, it more precisely represents economic activity. The disadvantage is that it does not contain a high level of detail on supply chain activities and, as discussed below, its definition of value added varies from traditional definitions. The Manufacturing Cost Guide has the advantage of having a high level of detail on the supply chain and manufacturing costs; however, some of the data and estimates are based on data from 2012. Fortunately, as shown in Thomas (2019b) these relationships change slowly; therefore, they are still largely relevant. More recent data with the same level of detail is not available, as there is typically a tradeoff between the level of detail in an economic dataset and the timeliness of the data.

Value added is the primary metric used to measure economic activity. The sum of all value added for a country is that nation's Gross Domestic Product (GDP). Since part of value added is compensation, we can use the SOC codes for labor to identify advanced biomanufacturing within the food and beverage industries. The following SOC codes are utilized to capture these activities:

- 191011 Animal Scientists
- 191012 Food Scientists and Technologists
- 191013 Soil and Plant Scientists
- 191021 Biochemists and Biophysicists
- 191022 Microbiologists
- 519010 Chemical Processing Machine Setters, Operators, and Tenders
- 194011 Agricultural and Food Science Technicians
- 194021 Biological Technicians
- 194031 Chemical Technicians
- 172021 Agricultural Engineers
- 173029 Engineering Technicians, Except Drafters, All Other

Estimates for compensation of these codes were taken from NIST's Manufacturing Cost Guide (Thomas 2019a). It is assumed that there is a 50 % overhead associated with advanced biomanufacturing labor and a multiplier of 1.5021 used for non-labor components (i.e., the other components of value added, including gross operating surplus and taxes), which was calculated using data from Table 3.1 in Thomas (2022):

$$1.5021 = 1 + \frac{Payroll, Benefits, and\ Employment}{Value\ Added\ Calculated} \tag{1}$$

The other values for advanced biomanufacturing of food and beverages are estimated by assuming the proportions between the value added estimated using labor, which is listed under the 2019 BEA value added in Table 5.1, are the same as that of the total industries.

The Annual Survey of Manufactures and the Economic Census, which on certain years is conducted in place of the Annual Survey of Manufactures, provide annual data on manufacturing including estimates of value added and shipments among other things. Their estimate of value added is equal to the value of shipments less the cost of materials, supplies, containers, fuel, purchased electricity, and contract work. It is adjusted by the addition of value added by merchandising operations plus the net change in finished goods and work-in-process goods.[4] As mentioned previously, value added avoids the duplication caused from the use of products of some establishments as materials. It is important to note that the BEA, which is a prominent source of data on value added, and the ASM calculate value added differently. The BEA calculates value added as "gross output (sales or receipts and other operating income, plus inventory change) less intermediate inputs (consumption of goods and services purchased from other industries or imported)."[5] Moreover, the difference is that ASM's calculation of value added includes purchases from other industries such as mining and construction while BEA's does not. Many would not consider ASM's estimate to be value added or would consider it to be direct value added along with some indirect value added.

All the industries in Table 5.1 were identified for biomanufacturing, which is consistent with those in the EU estimates for biomass producing and converting industries (Jurga et al. 2021; European Commission 2022). Note that this report focuses on manufacturing; thus, nonmanufacturing industries that are considered part of the bioeconomy are excluded. Some of the industries are only partially related to biomanufacturing. These include *manufacture of textiles*, *manufacture of wearing apparel*, *pharmaceutical and medicine manufacturing*, and *furniture and related product manufacturing*. For these industries, a proportion of the industry

[4] Census Bureau. 2020. "Annual Survey of Manufactures: Summary Statistics for Industry Groups and Industries in the U.S.: 2018 – 2020." https://www.census.gov/programs-surveys/asm.html
[5] Bureau of Economic Analysis. 2020. "Guide to the Interactive GDP-by-Industry Accounts Tables." https://www.bea.gov/resources/guide-interactive-gdp-industry-accounts-tables

Table 5.1: Estimated Manufacturing Value Added, Shipments, and Environmental Impact for Biomass Producing and Converting Industries

			2020 ASM Data		2019 Man. Cost Guide Estimates (Based on BEA Data)			2016 Estimates from Connely et al. 2020		2017 Estimates from Daystar et al. 2020 (excludes energy, food, feed, and pharmaceutical sectors)	
Description	NAICS	Percent of Industry Included (EU Definition)	Value Added ($Billion)	Shipments ($Billion)	Value Added ($Billion)	Total Direct and Indirect Value Added	Environ. Impact (percent of U.S. Impact) [5]	NAICS	Value Added	NAICS	Value Added
Manufacture of food products	311	100.00%	324.5	827.1	155.5	702.1	27.4				
Advanced Biomanufacturing of food [3]			9.0	22.9	4.3	19.4	0.8	311210, 221, 224, 225, 311300	3.0	311221, 311222, 311223, 311225, 311313, 311311, 311312	0.1
Manufacture of beverages	3121	100.00%	55.0	106.0	38.8	121.0	2.5				
Advanced Biomanufacturing of beverages/Tobacco [3]	312		4.0	7.7	2.8	8.8	0.2				
Manufacture of tobacco products	3122	100.00%	43.1	50.0	45.7	61.8	0.6				
Manufacture of textiles [1]	313, 314	27.04%	5.7	12.4	4.5	12.2	0.2			313, 314	9.6
Manufacture of wearing apparel [1]	315	40.98%	1.9	3.5	2.9	5.8	3.8			315	3.6
Manufacture of leather and related products	316	100.00%	2.0	4.0	3.0	7.5	0.1				
Wood product manufacturing	321	100.00%	54.7	117.7	26.5	76.2	2.2			321	28.2
Manufacture of paper and paper products	322	100.00%	81.8	180.3	57.5	147.8	3.4			322	58.9
								324110	8.4		
								32511	6.7		
Other Basic Organic Chemical	32519	100.00%	37.8	96.6	30.8	142.6	4.9	32519	11.9	32519	12.8
-Ethyl alcohol manufacturing	325193	100.00%	6.0	27.4							
-Cyclic crude intermediate and gum and wood chemical	325194	100.00%	2.6	4.9							

manufacturing											
-All other basic organic chemical manufacturing	325199	100.00%	29.2	64.3							
								3252, 3254-3259	161.4	3252, 3254-3259	17.7
Pharmaceutical and medicine [1]	3254	49.31%	84.5	114.0	53.4	78.9	0.3	3254	141.4	3254	12.6
-Medicinal and botanical	*325411*	*100.00%*	*8.2*	*13.1*	*6.8*	*13.3*	*0.1*				
-Pharmaceutical Preparation [4]	*325412*	*32.30%*	*59.6*	*50.0*	*24.6*	*42.4*	*0.2*	*325412*	*124.5*		
-In-Vitro Diagnostic Substance	*325413*	*32.30%*	*11.9*	*16.6*	*2.3*	*4.2*	*0.0*				
-Biological product (except diagnostic)	*325414*	*100.00%*	*30.5*	*46.8*	*18.1*	*26.4*	*0.1*	*325414*	*16.9*	*325414*	*12.6*
-Other [2]	*-*	*-*	*0.0 A*	*4.1*	*1.6*	*0.0 A*	*0.0*	*Other 325*	*20.0*	*Other 325*	5.1
Plastics and rubber products manufacturing [1]	326	4.62%	5.4	10.9	3.3	10.3	0.2	326	1.0	326	1.4
Furniture and related product manufacturing [1]	337	43.68%	16.5	30.1	9.7	28.8	0.6			337	16.0
-Wood kitchen cabinet and countertop	*33711*	*100.00%*	*8.9*	*14.6*	*5.1*	*11.9*	*0.2*			*33711*	*6.2*
-Non-upholstered wood household furniture	*337122*	*100.00%*	*1.5*	*3.1*	*1.5*	*4.5*	*0.1*			*337122*	*2.3*
-Office furniture	*33721*		*6.2*	*10.2*	*3.4 C*	*10.2 C*	*0.2 C*				
-Wood office furniture	*337211*	*100.00%*	*1.5*	*2.5*						*337211*	*1.5*
-Custom architectural woodwork and millwork	*337212*	*100.00%*	*4.7*	*7.7*						*337212*	*1.4*
-Other [2]	-	-	0.0 A	-8.0	0.0 A	0.0 A	0.0 A				
TOTAL (Biomanufacturing - EU Based Definition)			**725.8**	**1 583.3**	**438.8**	**1363.8 P T**	**43.0 P T**				
TOTAL (Advanced Biomanufacturing - NAS Based Definition)			**140.7**	**252.1**	**94.6**	**259.9**	**6.4**		**192.4**		

[1] Proportions drawn from Jurga, Piotr, Efstratios Loizou, and Stelios Rozakis. (2021). Comparing Bioeconomy Potential at National vs. Regional Level Employing Input-Output Modeling. Energies. 14. 1714. https://doi.org/10.3390/en14061714

[2] Calculated as the total for the main category less the other subcategories

[3] Estimated based on SOC 191011, 191012, 191013, 191021, 191022, 151111, 519010, 152021, 172041, 194011, 194021, 194031, 172021, 172041, and 173029 within NAICS 311/312 as noted in the text.

[4] Proportion drawn from Mikulic (2020)

[5] Weighted composite of twelve types of environmental impact reported in NIST's Manufacturing Cost Guide (2019a). Percent of total environmental impact resulting from economic activity in all U.S. industries

A - Adjusted to zero due to negative value

C - Calculated by estimating the impact for NAICS 33721 and multiplying it by the proportion 337211 and 337212 represent in NAICS 33721 in value added from the Annual Survey of Manufactures

P - Partial industries (NAICS 313, 314, 315, 3254, 326, 337, 337211, and 337212) were calculated seperately and added to the calculation for those with 100% creating some overlap. The overlap was removed by estimating the total overlap between partially included industries and those with 100% included.

T - Total does not equal sum due to overlap being excluded.

Blue – Partially included for advanced biomanufacturing Red - These industries are excluded from advanced biomanufacturing was included, which is estimated using proportions from Jurga et al. (2021). These proportions were estimated by surveying industry experts. Shipments and one of the estimates for value added in Table 5.1 are taken from the Annual Survey of Manufactures. Another estimate of value added along with an estimate of indirect value added (i.e., supply chain value added) and environmental impact is included, which is taken from NIST's Manufacturing Cost Guide (Thomas 2019a). These estimates rely on 2012 input-output data from the BEA and use the methods outlined in Appendix B. As mentioned previously, industry level data changes slowly; thus, this data is still relevant despite being from 2012. For the BEA data, some of the industries are grouped together (325193, 3251944 and 325199 are grouped; 337211 and 337212 are grouped).

The National Academy of Sciences (NAS) investigated the bioeconomy in Connely et al. (2020). Some results from this report are shown in two columns of Table 5.1. It is important to note that a number of these estimates are actually based on Daystar et al. (2020), which is presented in the last two columns of Table 5.1. The estimates in our report differ in a few ways from Connelly et al. (2020). The first is that the NAS report categorizes ethanol as *NAICS 324110*; however, this NAICS code is for petroleum refineries, which does not typically include ethanol, as it is included in *NAICS 325193 – Ethyl Alcohol Manufacturing*. Also in the NAS report is *NAICS 35211*, which is believed to be a typo for *NAICS 32511 – Petrochemical Manufacturing* (i.e., there is no *NAICS 35211*). Since this industry is defined as producing items from petroleum or liquid hydrocarbons, it is not included in our report's estimates, as this definition tends to exclude biological processes. *NAICS 32190* should capture both of the NAS categories that are used (*NAICS 324110* and *NAICS 32511*). When adding the NAS estimates for these two NAICS codes along with *NAICS 325190*, it is close to our BEA estimate for the total of *NAICS 325190*. Moreover, the difference described above might be interpreted as a difference in categorization.

Another difference between this report's estimates and the NAS report is found in *NAICS 325412 – Pharmaceutical Preparation Manufacturing* and *NAICS 325413 – In-Vitro Diagnostic Substance Manufacturing*. The NAS value for the former exceeds the total value added – including non-biomanufacturing – for the industry estimated using the BEA data from the Manufacturing Cost Guide (i.e., \$76.3 billion) and the ASM estimate for 2016 (i.e., \$118.0 billion). Recall that the ASM is an upper bound estimate, as it includes some supply chain items. Additionally, *NAICS 325412* specifically includes "in-vivo diagnostic substances and pharmaceutical preparations (except biological);" thus, because of the "except biological" statement, some portion of this industry is non-biological in nature. The NAS report states that, "biopharma… accounts for 25 percent of all pharmaceuticals." Given this assumption and the high value-added estimate for *NAICS 325412*, it is difficult to recreate the value added estimate found in the NAS report. Moreover, the NAS report estimate appears high for *NAICS 325412*.

The NAS report does not include an estimate for *NAICS 325413*, which is partially biological in nature, as it includes "diagnostic substances, such as chemical, biological, or radioactive substances." For our report, we utilize Mikulic (2020), which estimates that 32.3 % of pharmaceutical sales are biologics; thus, we apply this proportion to the two NAICS codes. The total difference between our report's estimate for all of *NAICS 3254* and the NAS estimate is significant and cannot be explained by differences in categorization. The NAS estimate is 165 % (\$88.0 billion) higher than our estimate, which accounts for most of the difference between our total advanced biomanufacturing estimate using BEA data (i.e., $94.6 billion) and the value using data drawn from the NAS report (i.e., $192.4 billion).

The last two columns present estimates from Daystar (2020), which specifies that it does not examine energy, livestock, food, feed, and pharmaceuticals. The exclusion of these accounts for much of the difference between this report's estimate of value added for advanced biomanufacturing and Daystar's (2020) values for the same industries. Given the differences in what is included, it is difficult to directly compare Daystar's values to the values in this report. However, some individual values can be compared and contrasted, many of which are similar.

In addition to value added, Table 5.1 provides an estimate of environmental impact by biomanufacturing and advanced biomanufacturing using NISTS's Manufacturing Cost Guide, which uses a weighted composite of twelve types of environmental impact discussed in Appendix B. The biomanufacturing industry impact accounts for 43 % of the total U.S. impact while advanced biomanufacturing is 6.4 %. For the former, food manufacturing (i.e., *NAICS 311*) accounts for the bulk of the impact. For the latter, much of the impact is in *NAICS 32519 – Other basic organic chemical manufacturing*.

6. Assets and Flow Time

The production of goods requires assets, such as machinery and buildings. The production of some goods can require more assets or more costly assets than other goods. Additionally, the flow rate of materials through the production process affects how many assets are required to produce a given amount of product in a given amount of time. Improving efficiency in a process might be achieved by reducing the cost of needed assets and/or increasing the flow of materials. Below is an examination of the assets and flow time for biomanufacturing.

6.1. Assets

Unfortunately, detailed data on depreciable assets is not annually reported. The most recent data on assets for biomanufacturing (i.e., data at the six-digit NAICS code level) is from the 2012 Economic Census. Table 6.1 provides the assets per dollar of value added along with the percentile for each of the Biomanufacturing NAICS codes. Those NAICS codes which are only partially included are not reported, as it would not be representative of biomanufacturing. The NAICS codes for advanced biomanufacturing has a high level of assets per dollar of value added, ranging between less than the 1st percentile to the 23rd percentile. Either a large volume of assets and/or very costly assets are required for advanced biomanufacturing.

6.2. Flow Time

Typically, a manufacturer desires or benefits from shorter flow times for materials. That is, all other things being equal, it is beneficial for products to be produced at a faster rate. If materials move more slowly through the manufacturing process, then the manufacturer needs more capital per unit of production. This report does not track the flow of physical goods directly, but rather tracks the monetary flow, which parallels the flow of physical goods (Meigs and Meigs, 1993, p. 991). This paper uses the term "flow time," but can also be referred to as throughput time, which is the time that elapses between buying raw materials for the production process and selling the finished product (Horngren et al., 2002). As discussed below, Thomas (2018a) lays out examining flow time at the industry and supply chain level.

The calculation for flow time can be thought of as water flowing through a pipe into a container. The cost of goods sold, $COGS$, is the total amount of water that runs into the container over a period of time and the inventory values are the amount of water in the pipe at any given time. Since we know the total amount of water that flowed out of the pipe (i.e., the amount in the container or $COGS$), we can estimate how many times the pipe was filled and emptied over that period of time (inventory turns or TRN) by dividing the amount in the container by the volume of the pipe. If one takes the number of days in a year and divides it by the number of inventory turns TRN, the result is the flow time FT, which represents the time it takes to move from the beginning to the end of the pipe. This method makes the assumption of first-in first-out (FIFO) where the oldest goods on hand are sold first (Meigs and Meigs, 1993). This paper breaks the industry inventory time into three categories: material goods, work-in-process, and finished

Table 6.1: Assets Required per Dollar of Value Added, 2012

Description	NAICS	Depreciable Assets per Dollar of Value Added	Percentile (Higher = Better or fewer assets per $ of value added)
Manufacture of food products	311	1.0	52.7
Advanced Biomanufacturing of food	-	-	-
Manufacture of beverages	3121	1.2	37.9
Advanced Biomanufacturing of beverages/Tobacco [3]	312	-	-
Manufacture of tobacco products	3122	0.2	99.5
Manufacture of textiles	313, 314	-	-
Manufacture of wearing apparel	315	-	-
Manufacture of leather and related products	316	0.9	61.9
Wood product manufacturing	321	1.7	15.9
Manufacture of paper and paper products	322	2.0	9.1
Ethyl alcohol manufacturing	325193	3.3	0.3
Cyclic crude intermediate and gum and wood chemical manufacturing	325194	3.2	0.8
All other basic organic chemical manufacturing	325199	2.7	2.3
Pharmaceutical and medicine manufacturing	3254	-	-
-Medicinal and botanical manufacturing	*325411*	*1.5*	*23.0*
-Pharmaceutical Preparation [4]	*325412*	-	-
-In-Vitro Diagnostic Substance	*325413*	-	-
-Biological product (except diagnostic) manufacturing	*325414*	*1.6*	*17.5*
-Other	-	-	-
Plastics and rubber products manufacturing	326	-	-
Furniture and related product manufacturing	337	-	-
-Wood kitchen cabinet and countertop manufacturing	*33711*	*0.8*	*65.5*
-Non-upholstered wood household furniture manufacturing	*337122*	*1.6*	*20.1*
-Wood office furniture manufacturing	*337211*	*0.8*	*73.9*
-Custom architectural woodwork and millwork manufacturing	*337212*	*0.7*	*79.4*
-Other	-	-	-

Blue – Partially included for advanced biomanufacturing Red - These industries are excluded from advanced biomanufacturing
Data source: U.S. Census Bureau (2021)

goods. For this reason, a ratio is included in the calculation to account for each category. The method for estimating the sum of the flow time for materials and supplies inventories, work-in-process inventories, and finished goods inventories for a particular industry, represented by NAICS codes, is the following:

$$FT_{\text{IND,Total}} = \frac{\left(INV_{\text{IND,i,BOY}} + INV_{\text{IND,i,EOY}}\right)/2}{\left(INV_{\text{IND,Total,BOY}} + INV_{\text{IND,Total,EOY}}\right)/2} \times \frac{365}{TRN_{\text{IND,Total}}} \tag{2}$$

where
$FT_{\text{IND,Total}}$ = Total estimated flow time for industry IND
i = Inventory item where i is materials and supplies (MS), work-in-process (WIP), or finished goods (FG) inventories.
$INV_{\text{IND,Total,BOY}}$ = Total inventory (i.e., materials and supplies, work-in-process, and finished goods inventories) for industry IND at the beginning of the year
$INV_{\text{IND,Total,EOY}}$ = Total inventory (i.e., materials and supplies, work-in-process, and finished goods inventories) for industry IND at the end of the year
$TRN_{\text{IND,Total}}$ = Inventory turns for industry IND (definedbelow)

This equation calculates and sums, for any industry, the flow time for materials and supplies inventories, work-in-process inventories, and finished goods. Calculating each of these stages is useful in identifying the source of the flow time (i.e., inventory time vs. work-in-process time). The days that a dollar spends in each of the inventory categories is being calculated by taking the total number of days in a year and dividing it by the number of inventory turns TRN, which is discussed below. This is then multiplied by average inventory of type i divided by the total inventory.

Inventory Turns: Inventory turns, TRN_{Total}, is the number of times inventory is sold or used in a time period such as a year (Horngren et al., 2002; Stickney and Brown, 1999; Hopp and Spearman). It is calculated as the cost of goods sold (COGS), which is the cost of the inventory that businesses sell to customers (Horngren et al., 2002), divided by the average inventory:

$$TRN_{\text{Total}} = \frac{COGS}{\left(\frac{INV_{\text{IND,Total,BOY}} + INV_{\text{IND,Total,EOY}}}{2}\right)} \tag{3}$$

where
$COGS = AP + FB + MAT + DEP + RP + OTH + \left(INV_{\text{Total,BOY}} - INV_{\text{Total,EOY}}\right)$
AP = Annual payroll
FB = Fringe benefits
MAT = Total cost of materials
DEP = Depreciation
RP = Rental payments
OTH = Total other expenses

Inventory turns is usually stated in yearly terms and is used to study a number of fields, such as distributive trade, particularly with respect to wholesaling (Hopp and Spearman, 2008). The data for calculating $COGS$ is from the Annual Survey of Manufacturing. In the previous two equations, inventories are calculated using the average of the beginning of year inventories and end of year inventories, which is standard practice (Horngren, et al., 2002).

For those NAICS codes that are not partially included in Table 5.1, an estimated flow time for material and supplies, work-in-process, and finished goods is provided in Table 6.2. It includes an estimate of the number of days that materials spend in each category (materials and supplies,

Table 6.2: Flow Time for Biomanufacturing and Advanced Biomanufacturing

Description	NAICS	Days in Inventory: Materials and supplies flow time	Days in Inventory: Work-in-process flow time	Days in Inventory: Work-in-process flow time (operation time)	Days in Inventory: Finished goods flow time	Percentile (Higher = better or shorter time): Materials and supplies flow time	Percentile: Work-in-process flow time	Percentile: Finished goods flow time
Manufacture of food products	311	11.9	3.5	1.8	16.3	92%	84%	70%
Advanced Biomanufacturing of food	-	-	-	-	-	-	-	-
Manufacture of beverages	3121	15.6	43.0	19.1	46.3	81%	7%	10%
Advanced Biomanufacturing of beverages/Tobacco [3]	312	-	-	-	-	-	-	-
Manufacture of tobacco products	3122	98.8	5.6	2.2	38.4	2%	68%	20%
Manufacture of textiles	313, 314	23.5	8.9	3.9	32.4	49%	53%	29%
Manufacture of wearing apparel	315	-	-	-	-	-	-	-
Manufacture of leather and related products	316	29.4	11.1	3.1	48.2	30%	42%	9%
Wood product manufacturing	321	20.1	6.6	2.1	18.9	65%	63%	62%
Manufacture of paper and paper products	322	18.0	3.2	1.8	15.0	72%	85%	74%
Ethyl alcohol manufacturing	325193	13.2	3.0	3.0	7.6	90%	85%	93%
Cyclic crude intermediate and gum and wood chemical manufacturing	325194	24.5	9.8	8.8	26.8	47%	48%	40%
All other basic organic chemical manufacturing	325199	17.1	5.5	4.6	27.2	76%	70%	38%
Pharmaceutical and medicine manufacturing	3254	28.9	29.3	11.7	60.1	32%	11%	5%
-Medicinal and botanical manufacturing	*325411*	*44.9*	*16.7*	*6.6*	*42.5*	*6%*	*27%*	*14%*
-Pharmaceutical Preparation [4]	*325412*	-	-	-	-	-	-	-
-In-Vitro Diagnostic Substance	*325413*	-	-	-	-	-	-	-
-Biological product (except diagnostic) manufacturing	*325414*	*23.3*	*47.1*	*18.7*	*51.8*	*50%*	*6%*	*8%*
-Other	-	-	-	-	-	-	-	-
Plastics and rubber products manufacturing	326	-	-	-	-	-	-	-
Furniture and related product manufacturing	337	-	-	-	-	-	-	-
-Wood kitchen cabinet and countertop manufacturing	*33711*	*16.7*	*8.1*	*2.0*	*8.4*	*78%*	*58%*	*91%*
-Non-upholstered wood household furniture manufacturing	*337122*	*27.0*	*9.5*	*2.4*	*35.8*	*36%*	*50%*	*22%*
-Wood office furniture manufacturing	*337211*	*22.9*	*4.2*	*1.2*	*7.0*	*53%*	*81%*	*94%*
-Custom architectural woodwork and millwork manufacturing	*337212*	*15.3*	*14.5*	*4.2*	*12.7*	*82%*	*33%*	*81%*
-Other	-	-	-	-	-	-	-	-
Mean	**311111-339999**	**24.8**	**14.1**		**25.7**			
Max	**311111-339999**	**98.8**	**326.8**		**129.7**			
Min	**311111-339999**	**1.8**	**0.2**		**0.2**			
Median	**311111-339999**	**23.1**	**9.3**		**23.0**			

Blue – Partially included for advanced biomanufacturing Red - These industries are excluded from advanced biomanufacturing

Data source for calculations: U.S. Census Bureau (2021) work-in-process, and finished goods) along with the percentile, where a higher percentile means it is less time. The manufacture of food, for instance, is at the 92nd, 84th, and 70th percentiles for materials and supplies, work-in-process, and finished goods respectively. This means that the materials and supplies inventory time for food products is shorter than 92 % of all manufacturing industries while work-in-process is shorter than 84 % and finished goods is shorter than 70 %. Food manufacturing would be expected to have shorter inventory times, as these are perishable items; thus, the high percentile is consistent with expectations.

Pharmaceutical and medicine manufacturing is among the slowest with work-in-process times being between the 6th and 27th percentile. Materials and supplies along with finished goods inventories have similarly slow flow times. This means that materials are using capital (e.g., machinery) for a long period of time when compared to other manufacturing industries. Many, but not all, of the biomanufacturing industries that are not advanced biomanufacturing have shorter work-in-process flow times. However, beverage manufacturing, leather and related product manufacturing, and custom architectural woodwork and millwork manufacturing had longer flow times being at the 7th, 42nd, and 33rd percentiles.

It is important to note that the work-in-process time includes downtime when the factory is closed. For this reason, Table 6.2 also has a column labeled “Work-in-process flow time (operation time).” This is the Work-in-process time multiplied by the average proportion of the week that the manufacturing facilities are operating. This is calculated from the “2012 Quarterly Survey of Plant Capacity Utilization,” which includes the “Average Plant hours per week in operation” (U.S. Census Bureau 2012). In some instances, there was data available for the NAICS codes listed in Table 6.2. In some cases, the average of subcategories within a NAICS category are used. For instance, the average of multiple six-digit NAICS might be used for a five-digit NAICS code listed in Table 6.2. In other instances, a broader NAICS code was used. For instance, a five-digit NAICS code might be used for a six-digit code. Because there are not perfect matches for each NAICS code, the table does not compare the “work-in-process flow time (operation time)” to other NAICS by listing the percentile that it falls into.

7. Biomanufacturing Supply Chains and Energy Consumption

At the industry level, input-output analysis can provide significant insight into industry supply chains. However, this method separates inputs into separate industries. Thus, it can be useful to examine some items separately. An input-output analysis of biomanufacturing industries is presented below along with a discussion of energy consumption.

7.1. Supply Chains and Input-Output Analysis

Using input-output analysis outlined in Appendix B, an examination of the supply chain for biomanufactured products was conducted. This reveals the industry activities embedded in biomanufactured products. This method assumes that industries consume inputs in fixed proportions. Only the industries where 100 % is included from Table 5.1 is examined, as an examination of other industries would reveal information regarding a combination of biomanufactured and non-biomanufactured products. The highest 20 % of supply chain items based on the total of value added and impacts is shown for each NAICS code for biomanufacturing in Appendix C through Appendix H:

- Appendix C. Food, Beverage, and Tobacco Manufacturing Supply Chain (NAICS 311 and 312)
- Appendix D. Leather Supply Chain (NAICS 316)
- Appendix E. Paper and Wood Product Supply Chain (NAICS 321 and 322)
- Appendix F. Other Basic Organic Chemical Manufacturing Supply Chain (NAICS 325190)
- Appendix G. Select Pharmaceutical and Medicine Manufacturing Supply Chain (NAICS 325411 and 325414)
- Appendix H. Select Furniture and Related Product Manufacturing Supply Chain (NAICS 33711 and 337122)

For food, beverage, and tobacco manufacturing, the largest item is in the category of wholesalers, as is the fourth largest; thus, efficiency improvements in the wholesale industry might have a significant effect on food, beverage, and tobacco manufactured goods. Electric power generation and multiple forms of transportation appear in the list as well. These three items appear near the top of the list for all the industries examined. Fifteen supply chain industries appeared in all the industries:

- 115000 Support activities for agriculture and forestry
- 325211 Plastics material and resin manufacturing
- 332710 Machine shops
- 334413 Semiconductor and related device manufacturing
- 423A00 Other durable goods merchant wholesalers
- 423800 Machinery, equipment, and supplies
- 424A00 Other nondurable goods merchant wholesalers
- 424700 Petroleum and petroleum products
- 425000 Wholesale electronic markets and agents and brokers
- 481000 Air transportation

- 482000 Rail transportation
- 484000 Truck transportation
- 531ORE Other real estate
- 532400 Commercial and industrial machinery and equipment rental and leasing
- 5419A0 All other miscellaneous professional, scientific, and technical services

7.2. Energy

Although the input-output analysis in Section 7.1 includes energy costs, it breaks apart some of the components of energy, such as the extraction of raw materials for energy production. The Annual Survey of Manufactures provides an estimate of purchased fuels and electricity and is provided in Table 7.1, which also includes the percentile for each industry. For clarity, note that fuels do not include electricity. A higher percentile means lower costs. A number of advanced biomanufacturing industries have a relatively high level of energy consumption, including *ethyl alcohol manufacturing, cyclic crude intermediate and gum and wood chemical manufacturing,* and *other basic organic chemical manufacturing*.

Table 7.1: Purchased Fuels and Electricity

Description	NAICS	Cost of purchased fuels ($million)	Cost of purchased electricity ($million)	Purchased fuels per dollar of value added, percentile (Higher = better or less cost)	Purchased electricity per dollar of value added, percentile (Higher = better or less cost)
Manufacture of food products	311	3886.6	5509.3	22.0	37.0
Advanced Biomanufacturing of food	-	-	-	-	-
Manufacture of beverages	3121	324.7	687.2	46.1	62.2
Advanced Biomanufacturing of beverages/Tobacco [3]	312	-	-	-	-
Manufacture of tobacco products	3122	37.2	70.4	94.9	99.7
Manufacture of textiles	313, 314	-	-	-	-
Manufacture of wearing apparel	315	-	-	-	-
Manufacture of leather and related products	316	8.6	28.4	60.7	61.1
Wood product manufacturing	321	501.4	1405.1	21.4	10.6
Manufacture of paper and paper products	322	3721.2	3580.5	7.9	13.2
Ethyl alcohol manufacturing	325193	1441.2	627.6	0.3	1.6
Cyclic crude intermediate and gum and wood chemical manufacturing	325194	125.6	138.3	10.3	13.5
All other basic organic chemical manufacturing	325199	1781.2	925.1	5.1	25.7
Pharmaceutical and medicine manufacturing	3254	-	-	-	-
-Medicinal and botanical manufacturing	*325411*	*75.9*	*125.1*	*34.4*	*55.0*
-Pharmaceutical Preparation [4]	*325412*	-	-	-	-
-In-Vitro Diagnostic Substance	*325413*	-	-	-	-
-Biological product (except diagnostic) manufacturing	*325414*	*101.7*	*143.7*	*53.7*	*90.7*
-Other	-	-	-	-	-
Plastics and rubber products manufacturing	326	-	-	-	-
Furniture and related product manufacturing	337	-	-	60.4	64.8
-Wood kitchen cabinet and countertop manufacturing	*33711*	*34.8*	*99.1*	*50.1*	*52.6*
-Non-upholstered wood household furniture manufacturing	*337122*	*14.5*	*42.6*	*42.0*	*39.7*
-Wood office furniture manufacturing	*337211*	*5.8*	*23.6*	*66.9*	*55.6*
-Custom architectural woodwork and millwork manufacturing	*337212*	*12.7*	*44.6*	*66.7*	*63.8*
-Other	-	-	-	-	-

Blue – Partially included for advanced biomanufacturing Red - These industries are excluded from advanced biomanufacturing

8. Investment Returns in Biomanufacturing Efficiency Improvements

This section presents an examination of the returns from investments in the IAC database. It is a publicly available database of 148 000 recommendations for 20 000 facilities, as of October 2021. The data is the result of DOE technical assessments of facilities conducted by university engineering students and staff from 26 IACs made up of 31 universities (Industrial Assessment Center 2021; U.S. Department of Energy 2011). Each observation in the IAC database is a recommendation for an investment. It includes an Assessment Recommendation Code (ARC) (discussed below), the cost to implement the recommendation, estimated annual savings, year, whether the recommendation was implemented, and some characteristics of the establishment including sales, various energy expenditures, and number of employees. For the IAC to conduct an assessment, a facility must generally have the following: gross annual sales of $100 million or less, consume energy at a cost greater than $100 000 and less than $2.5 million per year, employ no more than 500 people, and have no technical staff whose primary duty is energy analysis (U.S. Department of Energy 2011). These requirements suggest that the facilities being examined are likely to have a relatively higher level of low-cost, high-return investment possibilities, as these establishments have higher costs (i.e., energy costs) and fewer resources to identify potential investments. The final selection is left up to the individual IACs. Two categorization systems are used in the IAC database. The first is the NAICS codes and the second is the ARC.

The ARC codes have between one and five digits with a total of approximately 424 codes. Similar to NAICS codes, more digits represent additional detail. There are three single digit codes: ARC 2 - energy management; ARC 3 – waste minimization / pollution prevention; ARC 4 – direct productivity enhancements. Additional detail is indicated in numbers to the right of the decimal. For instance, ARC 2.4157, which is within ARC 2, is "ESTABLISH A PREDICTIVE MAINTENANCE PROGRAM." For simplicity among standard codes used in this analysis, we remove the decimal and add zeros for place holders, making it similar to NAICS code structure. Thus, ARC 2.4 is reported as 24000. This leaves one concept for understanding the hierarchy and reveals the maximum level of detail.

This report uses net present value (NPV) and internal rate of return (IRR) to assess the economics of an investment. To compare cash flows at different time periods, future cash flow is *discounted* to equate to a common time period (Thomas 2017; Ross et al. 2005; Defusco et al. 2015). NPV is calculated by summing cash inflows and subtracting cash outflows for each year and adjusting it, using a discount rate, to a common time period, which we will call time zero (Thomas 2017):

$$NPV = \sum_{t=0}^{T} \frac{(I_t - C_t)}{(1+r)^t} \tag{4}$$

I_t = Total cash inflow in time period t
C_t = Total cost in time period t
r = Discount rate
t = Time period, which is typically measured in years

Table 8.1 provides the percentile of the net present value by ARC for the biomanufacturing industries for which data was available. High values equate to higher NPV. Those above the 80th percentile are highlighted in green and represent areas that may have increased opportunity for efficiency improvements in existing processes. Combustion systems, thermal systems, electrical power, and motor systems have several categories with a high NPV. Appendix I provides the aggregated NPV at the five-digit level. The top six items, which includes all those above the 95th percentile, for *NAICS 325190 – Basic organic Chemicals* are the following:

- 21212 Combustion Systems - BOILERS - OPERATE BOILERS ON HIGH FIRE SETTING
- 22414 Thermal Systems - HEAT RECOVERY - USE WASTE HEAT FROM HOT FLUE GASES TO PREHEAT
- 22437 Thermal Systems - HEAT RECOVERY - RECOVER WASTE HEAT FROM EQUIPMENT
- 23131 Electrical Power - DEMAND MANAGEMENT - RESCHEDULE PLANT OPERATIONS OR REDUCE LOAD TO AVOID PEAKS
- 23415 Electrical Power - COGENERATION - USE A FOSSIL FUEL ENGINE TO COGENERATE ELECTRICITY OR MOTIVE POWER; AND UTILIZE HEAT
- 23417 Electrical Power - COGENERATION - USE WASTE HEAT WITH A CLOSED-CYCLE GAS TURBINE-GENERATOR SET TO COGENERATE ELECTRICITY AND HEAT

Three of these are reusing waste heat. For pharmaceuticals, the top eight, which includes all those above the 95th percentile, includes the following

- 22423 Thermal Systems - HEAT RECOVERY - INSTALL WASTE HEAT BOILER TO PRODUCE STEAM
- 22622 Thermal Systems - COOLING - REPLACE EXISTING CHILLER WITH HIGH EFFICIENCY MODEL
- 24146 Motor Systems - MOTORS - USE ADJUSTABLE FREQUENCY DRIVE OR MULTIPLE SPEED MOTORS ON EXISTING SYSTEM
- 27142 Building and Grounds - LIGHTING - UTILIZE HIGHER EFFICIENCY LAMPS AND/OR BALLASTS
- 27313 Building and Grounds - VENTILATION - RECYCLE AIR FOR HEATING, VENTILATION AND AIR CONDITIONING
- 27425 Building and Grounds - BUILDING ENVELOPE - CLEAN OR COLOR ROOF TO REDUCE SOLAR LOAD
- 33128 Post Generation Treatment / Minimization - GENERAL - UTILIZE OTHER METHODS TO REMOVE CONTAMINANTS
- 36193 Waste Disposal - GENERAL - INSTALL EQUIPMENT (E.G. COMPACTOR) TO REDUCE DISPOSAL COSTS

One item to note is in regard to addressing contaminants in waste (i.e., ARC 33128). Additionally, issues regarding building lighting, heating, and cooling are listed along with heat recovery and waste disposal.

Table 8.1: Percentile of Aggregate Net Present Value (NPV) by 3 Digit ARC Code

ARC Code, Two Digit Description, Three Digit Description	Food, Beverage, Tobacco, and Leather	Paper and Wood	Basic Organic Chemicals	Pharmaceuticals and Medicine	Furniture and Related Product
211 Combustion Systems - FURNACES, OVENS & DIRECTLY FIRED OPERATIONS	56.9	74.2	32.3	35.0	-
212 Combustion Systems - BOILERS	86.2	82.3	93.5	70.0	-
213 Combustion Systems - FUEL SWITCHING	90.8	83.9	67.7	60.0	-
221 Thermal Systems - STEAM	92.3	91.9	87.1	67.5	-
222 Thermal Systems - HEATING	33.8	30.6	77.4	2.5	-
223 Thermal Systems - HEAT TREATING	27.7	14.5	-	-	-
224 Thermal Systems - HEAT RECOVERY	98.5	98.4	96.8	97.5	-
225 Thermal Systems - HEAT CONTAINMENT	69.2	64.5	64.5	32.5	-
226 Thermal Systems - COOLING	89.2	51.6	74.2	80.0	-
227 Thermal Systems - DRYING	30.8	3.2	12.9	-	-
231 Electrical Power - DEMAND MANAGEMENT	67.7	61.3	80.6	42.5	-
232 Electrical Power - POWER FACTOR	66.2	58.1	35.5	40.0	-
233 Electrical Power - GENERATION OF POWER	47.7	46.8	71.0	-	-
234 Electrical Power - COGENERATION	81.5	93.5	90.3	52.5	-
235 Electrical Power - TRANSMISSION	9.2	11.3	-	17.5	-
241 Motor Systems - MOTORS	96.9	90.3	83.9	85.0	-
242 Motor Systems - AIR COMPRESSORS	95.4	88.7	58.1	75.0	-
243 Motor Systems - OTHER EQUIPMENT	83.1	77.4	19.4	47.5	-
251 Industrial Design - SYSTEMS	60.0	59.7	41.9	62.5	-
261 Operations - MAINTENANCE	24.6	48.4	-	22.5	-
262 Operations - EQUIPMENT CONTROL	76.9	71.0	38.7	72.5	-
271 Building and Grounds - LIGHTING	93.8	87.1	61.3	90.0	-
272 Building and Grounds - SPACE CONDITIONING	70.8	67.7	45.2	95.0	-
273 Building and Grounds - VENTILATION	40.0	53.2	25.8	87.5	-
274 Building and Grounds - BUILDING ENVELOPE	64.6	50.0	6.5	77.5	-
281 Ancillary Costs - ADMINISTRATIVE	75.4	62.9	16.1	65.0	-
282 Ancillary Costs - SHIPPING, DISTRIBUTION, AND TRANSPORTATION	43.1	40.3	-	-	-
291 Alternative Energy Usage - GENERAL	63.1	0.0	0.0	0.0	-
311 Operations - PROCEDURES	72.3	79.0	29.0	20.0	-
312 Operations - WASTE STREAM CONTAMINATION	13.8	37.1	-	-	-
321 Equipment - GENERAL	38.5	12.9	-	45.0	-
331 Post Generation Treatment / Minimization - GENERAL	61.5	16.1	48.4	82.5	-
341 Water Use - GENERAL	80.0	41.9	54.8	55.0	-
351 Recycling - LIQUID WASTE	26.2	21.0	-	-	-
352 Recycling - SOLID WASTE	20.0	29.0	3.2	27.5	-
353 Recycling - OTHER MATERIALS	53.8	54.8	9.7	15.0	-
361 Waste Disposal - GENERAL	49.2	56.5	-	92.5	-
371 Maintenance - CLEANING / DEGREASING	12.3	4.8	-	-	-

372 Maintenance - SPILLAGE	29.2	6.5	-	-	-
373 Maintenance - OTHER	16.9	8.1	-	-	-
381 Raw Materials - SOLVENTS	32.3	19.4	-	-	-
382 Raw Materials - OTHER SOLUTIONS	4.6	-	-	-	-
383 Raw Materials - SOLIDS	-	-	-	-	-
411 Manufacturing Enhancements - BOTTLENECK REDUCTION	84.6	96.8	51.6	57.5	-
412 Manufacturing Enhancements - DEFECT REDUCTION	52.3	66.1	-	-	-
413 Manufacturing Enhancements - MATERIAL REDUCTION	55.4	75.8	-	-	-
421 Purchasing - RAW MATERIALS	0.0	35.5	22.6	-	-
422 Purchasing - ANCILLARY MATERIALS	15.4	-	-	-	-
423 Purchasing - CAPITAL	3.1	25.8	-	-	-
431 Inventory - JUST IN TIME	6.2	-	-	-	-
432 Inventory - OTHER INVENTORY CONTROLS	35.4	38.7	-	10.0	-
442 Labor Optimization - PRACTICES / PROCEDURES	36.9	69.4	-	37.5	-
443 Labor Optimization - TRAINING	58.5	45.2	-	-	-
444 Labor Optimization - AUTOMATION	87.7	80.6	-	30.0	-
445 Labor Optimization - SCHEDULING	46.2	85.5	-	-	-
446 Labor Optimization - MAINTENANCE	18.5	9.7	-	-	-
451 Space Utilization - FLOOR LAYOUT	44.6	0.0	-	-	-
452 Space Utilization - RENTAL SPACE	41.5	32.3	-	5.0	-
461 Reduction of Downtime - MAINTENANCE	50.8	33.9	-	7.5	-
462 Reduction of Downtime - QUICK CHANGE	7.7	72.6	-	-	-
463 Reduction of Downtime - POWER CONDITIONING	78.5	27.4	-	-	-
464 Reduction of Downtime - ALARMS	1.5	43.5	-	-	-
465 Reduction of Downtime - OTHER EQUIPMENT	73.8	95.2	-	50.0	-
466 Reduction of Downtime - INDUSTRIAL INTERNET OF THINGS SENSORS (IIOT)	21.5	-	-	-	-
471 Management Practices - TOTAL QUALITY MANAGEMENT	-	17.7	-	-	-
472 Management Practices - CERTIFICATIONS	-	-	-	-	-
473 Management Practices - MARKETING	-	-	-	-	-
481 Other Administrative Savings - TAXES	23.1	22.6	-	25.0	-
482 Other Administrative Savings - FEES	10.8	24.2	-	12.5	-

9. Data Gaps

Although there are several sources of data covering a range of issues in biomanufacturing, there are some data gaps. For instance, biopharmaceutical API's can be produced using one of three manufacturing methods: batch process, fed-batch process, or a continuous process (Allman 2020). A batch process includes adding all the needed materials to a container at the beginning of a process step. The material is grown in the container and then transferred to another container for a subsequent process step. A fed-batch process is similar but adds materials at different points in the process to increase the effectiveness. Finally, a continuous process has sequential input and sequential output of materials, resulting in a flow of product. There is limited data on the extent to which these three methods are used. There are also different advantages/disadvantages to each method, as shown in Table 9.1. For instance, batch processes and fed-batch processes tend to have higher downtime, particularly between batches, resulting in lower productivity. These processes, however, have a lower risk of contamination, as materials are not being constantly fed into the bioreactor. They also have greater traceability if a batch is contaminated along with increased flexibility in producing different types of biomaterial in the same vessel, if or when possible. It is unclear to what extent contamination occurs, the amount of losses resulting from contamination, or the amount of downtime between batches, among other things.

Table 9.1: Advantages and Disadvantages of Batch, Fed-batch, and Continuous Biopharmaceutical Manufacturing of API's

	Batch Process	Fed-Batch Process	Continuous Process
Productivity	Low	Medium	High
Downtime	High	High	Low
Contamination Risk	Low	Medium	High
Traceability	High	High	Low
Agility (ability to increase/decrease production rate)	Low	Low	High
Flexibility	High	High	Low

NOTE: Red indicates relatively unfavorable conditions, orange is relatively moderate conditions, and green indicates relatively more favorable conditions

After the API material is obtained, it is then produced into capsules, tablets, liquid, sterile injections, or other forms of delivery. These products then move to filling and/or packaging, depending on the form of the material (e.g., liquid or powder). According to a former machinery maintenance employee at a major pharmaceutical manufacturer, machinery in packaging can last 10 years to 15 years with some being as much as 30 years old. They primarily rely on preventive maintenance (i.e., maintenance based on cycles or time) taking place during downtime, as opposed to predictive maintenance (i.e., maintenance based on sensor data) or reactive maintenance (i.e., run to failure). Some packaging lines might run 100 % of the time (i.e., 24 hours per day, 7 days a week) while others might only run around 25 % of the time (e.g., one shift per day), depending on needs. Different types of machinery are used for different types of packaging. For instance, some products go into bottles while others might go into blister packages (see Figure 9.1). Lines might breakdown once every six to nine months, depending on how much machinery a line has and the level of complexity of the machinery. Typically, they would be down only an hour, but on occasion it could be as much as a few days.

Figure 9.1: Illustration of Blister Packages

Change overs for packaging one product to another can take between 3 hours to 16 hours, depending on the changes needed. The number of people needed for packaging has decreased over time. For instance, between 1984 and 2000, the number of people needed to operate a packaging line for a particular pain reliever went from about approximately 32 to 6 with many of these people being replaced with sensors. For instance, an employee would watch to ensure that the right number of capsules are put into the bottle, another to ensure the cotton is inserted, and another to ensure the cap is put on correctly. These activities are now completed using sensors.

The information provided above is only anecdotal. At the industry level, it is not clear how much time is downtime, how often machinery breaks down, where processes might benefit from additional sensors, or how often materials need to be repackaged or discarded due to machinery/human error. Similar knowledge gaps exist for other biomanufactured goods (e.g., food and furniture) as well. The following data gaps were identified for biomanufacturing:

- Batches
    - Data on the percent of biomanufactured goods produced in batches, fed-batch, and continuous production.
    - For those goods produced in batches, data on the downtime between batches.
    - The percent of biomanufactured goods lost (e.g., contaminated).
        - Data on the cause of these losses.
- Supply chains
    - Data on the production losses due to supply chain disruption.
    - Data on the supply chain disruption causes.
    - Data on the geographic origins of supplies
- Data/Communication
    - Data on information/data communication errors.

    - Delivery errors between stages/supply chains
    - Data on language mismatches that result in data being entered manually.
- Feedstocks and Material Inventory
    - Data on feedstock and other material inventory that is lost (e.g., spoiled).
        - Data on the causes of these losses (e.g., spoiled or contaminated).
- Finished Goods Inventory
    - Data on the percent of finished biomanufactured goods lost/disposed.
        - Data on the causes of these losses (e.g., spoiled or contaminated).
- Machinery Maintenance
    - Data on maintenance costs.
    - Data on machinery breakdowns or needed repairs.
        - Data on the consequences/losses of machinery breakdowns.
- Reprocessing
    - Data on material that needs to be reprocessed or repackaged due to errors
- Changeovers
    - Data on the time and costs for changeovers
- Environmental impacts
    - Data on the environmental impacts of various processes, including packaging
- Redundancy
    - Data on machinery that remains idle
- Cyber Security
    - Costs and losses to cyber attacks
- New products
    - Costs, losses, and risks associated with developing new products
- Identifying Biomanufactured Goods
    - Industry data, including value added, supply chains, assets, flow time, and energy consumption for the portions of the following industries and NAICS codes that are biomanufacturing: textiles (313 and 314), wearing apparel (315), pharmaceutical preparations (325412), in-vitro diagnostic substances (325413), other biomanufactured chemicals (325), and plastics (326).
    - Industry data, including value added, supply chains, assets, flow time, and energy consumption for the portions of the following industries and NAICS codes that are advanced biomanufacturing: food (311) and beverages (312).

There might be literature on some of the data gaps listed above. To determine whether there is literature available, industry focused research is needed. The area of biomanufacturing includes a broad array of manufacturing activities from biofuels to food, biopharmaceuticals, and furniture manufacturing. From the vast array of materials, processes, and products that are included in biomanufacturing, it is likely that separate studies are needed for the different products. The missing data could be collected through surveys sent to manufacturers; however, some items are complex (e.g., supply chain data) and some items might not be collected directly. For statistically significant findings, a minimum sample size is needed. The sample size needed for estimating the mean of a population can be represented as (NIST 2012):

$$Sample\ Size = \left(\frac{z\sigma}{e}\right)^2 \tag{5}$$

where
σ = Standard deviation
e = Nominal Margin of error (mean multiplied by percent margin of error)
z = z-score

A previous analysis by Thomas (2018c) examined the sample size needed for collecting data on maintenance in manufacturing. The actual sample size cannot be estimated, as it depends on characteristics of the data that are unknown until the data is collected and examined. Since maintenance is one of the items listed above as missing, we can utilize this as an example for a required sample size. From Thomas (2018c), the annual Survey of Manufactures estimates the total value of manufacturing maintenance was $49.5 billion for 292 825 establishments with a sample size estimated at approximately 50 000, resulting in a standard deviation of $75 627, as calculated by:

$$\sigma = \frac{RSE}{100} * \frac{M\&R}{EST} * \sqrt{SPL} \tag{6}$$

where
RSE = Relative standard error from the Annual Survey of Manufactures
$M\&R$ = Repair and maintenance services of buildings and/or machinery from the Annual Survey of Manufactures
EST = Number of establishments in manufacturing from the County Business Patterns data
SPL = Approximate sample size of the Annual Survey of Manufactures

Assuming a percent margin of error of 10 % (note that equation 5 uses a nominal value as the margin of error that is calculated from the percent) and a 95 % confidence interval (i.e., z = 1.96), the sample size required is calculated to be 77. Figure 9.2 graphs the various sample sizes required at different confidence intervals and margins of error with the standard deviation equaling $75 627. With a margin of error of 20 % and a confidence interval as low as 90 %, as few as 14 samples are required.

Since the assessment of sample size relies on several assumptions, a probabilistic sensitivity analysis was conducted using Monte Carlo analysis. This technique is based on works by McKay, Conover, and Beckman (1979) and Harris (1984) that involves a method of model sampling. It was implemented using the Crystal Ball software product (Oracle 2013), an add-on for spreadsheets. Specification involves defining which variables are to be simulated, the distribution of each of these variables, and the number of iterations performed. The software randomly samples from the probabilities for each input variable of interest. The population, value of maintenance/repair, relative standard error, sample size from the Annual Survey of Manufacturers, and the samples size needed for this study were each varied using a triangular distribution with the parameters shown in Table 9.2. The z-score was varied between a 99 % confidence interval and a 90 % confidence interval. These variations allow for relatively large

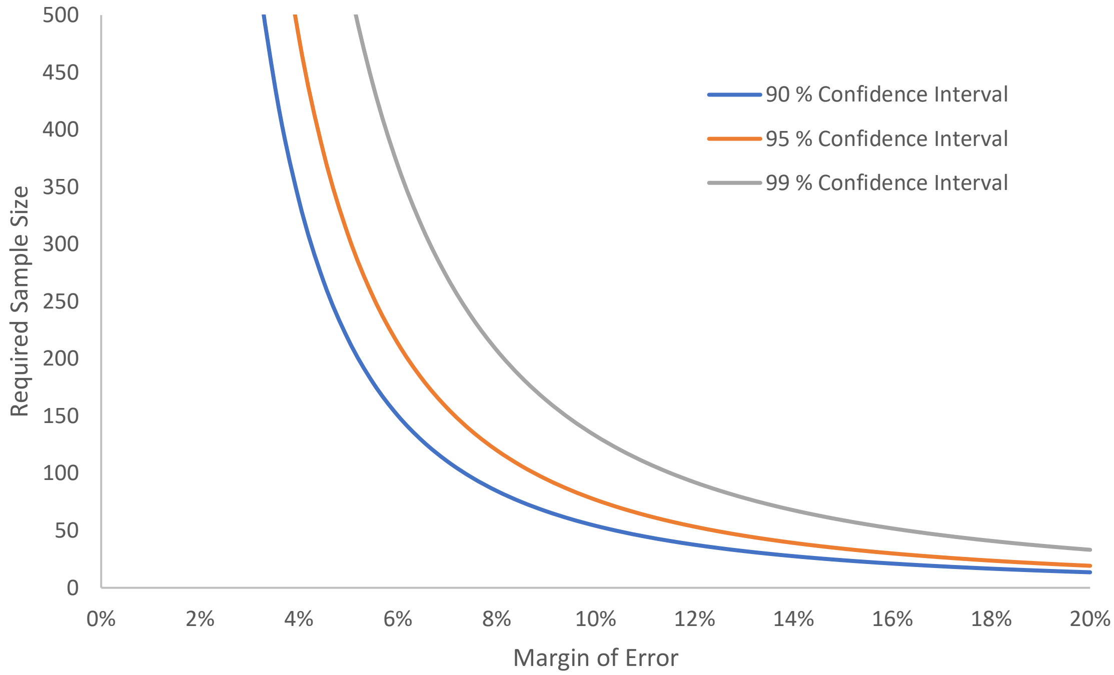


Figure 9.2: Required Sample Size by Margin of Error and Confidence Interval
Note: Standard deviation equals 75 627, as calculated from the Annual Survey of Manufactures

error in the assumptions for calculating the sample size and margin of error, as the standard deviation for maintenance cost ranges from a little less than 65 000 to more than 630 000.

A cumulative probability graph of the results is shown in Figure 9.3, which shows that for 80 % (i.e., a cumulative probability of 0.8) of the iterations the margin of error is below 0.52 (+/-52 % in estimating maintenance cost), as illustrated with dotted lines in the figure. Figure 9.4 graphs the margin of error for those iterations in the Monte Carlo analysis that are at the 90 % confidence interval. As seen in the figure, the standard deviation has significant impact on the margin of error; thus, the accuracy of the assumptions has a substantial effect.

Table 9.2: Assumptions for Monte Carlo Analysis (Triangular distributions)

	Min	Most Likely	Max
Population (establishments)	248 901 (-15 %)	292 825	336 749 (+15 %)
Value of M&R	44.6 billion (-10 %)	49.5 billion	54.5 billion (+10 %)
Relative Standard Error	0.2	0.2	1.5
Sample Size (ASM)	40000	50000	55000
Sample Size (Needed)	20	40	150
z-score (uniform distribution)	1.65	-	2.58

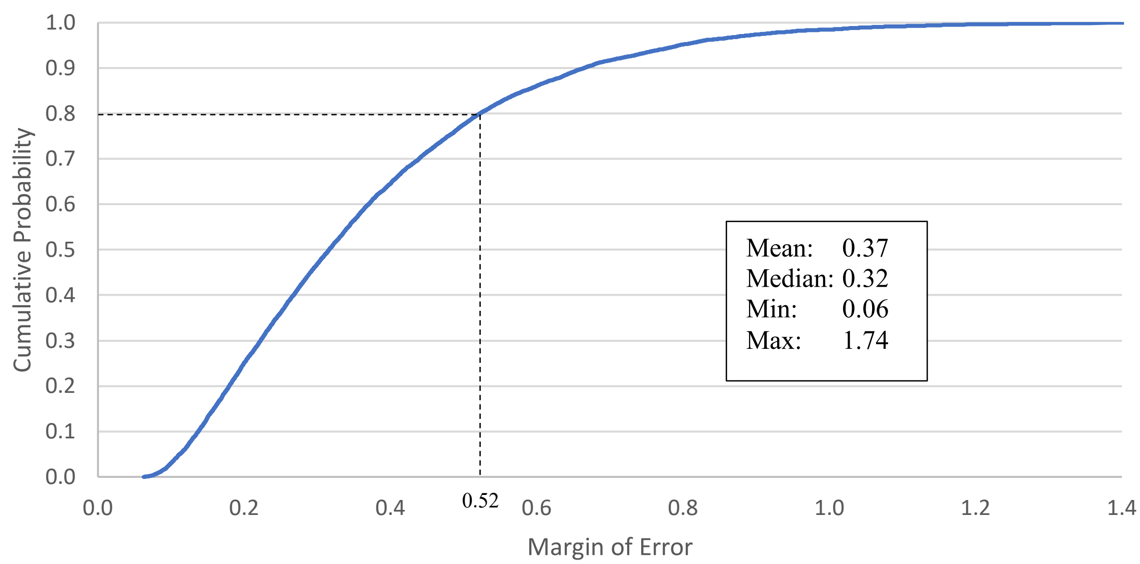


Figure 9.3: Cumulative Frequency Graph, Monte Carlo Analysis

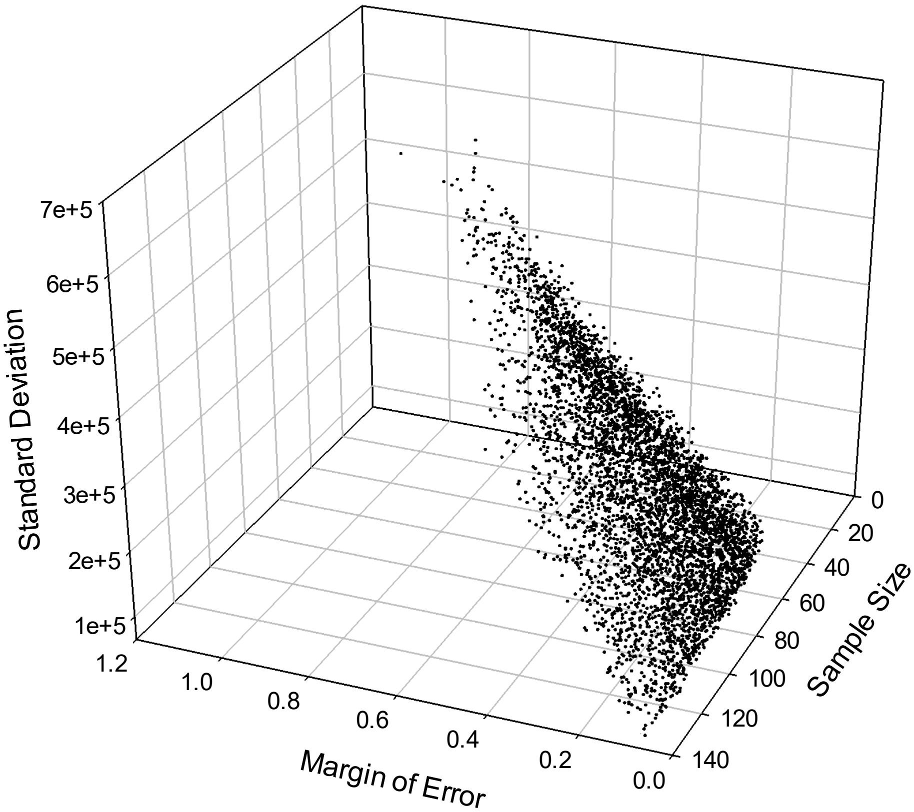


Figure 9.4: Margin of Error Graphed with Standard Deviation of Maintenance Cost and Sample Size from Monte Carlo Analysis (90 % Confidence Interval only)

10. Summary

The biomanufacturing industry includes a wide array of activities. There are two general definitions of the bioeconomy. A broader definition is found in the European Union and a narrower definition found in the United States. For this report, the broad definition is used to identify “biomanufacturing” while the narrow definition is used to identify “advanced biomanufacturing.” This report estimates biomanufacturing and advanced biomanufacturing value added in ways consistent with estimates of U.S. GDP. Advanced biomanufacturing is estimated as being $94.6 billion while total biomanufacturing is $438.8 billion. When including supply chain items and other indirect value added, the total biomanufacturing industry is $1363.8 billion and advanced biomanufacturing is $259.9 billion. These estimates include biomanufacturing items that are excluded from some estimates. Other U.S. estimates have also been inconsistent with measures of GDP value added. As calculated using NIST’s Manufacturing Cost Guide, the biomanufacturing industry environmental impact accounts for 43 % of the total environmental impact resulting from economic activity in all U.S. industries while advanced biomanufacturing is 6.4 %.

This report also examines the assets, material flow time, fuels, and electricity used in biomanufacturing. Some of the industries in biomanufacturing require a disproportional amount of assets, have longer flow times, and/or require relatively large amounts of energy. Despite the items measured in this report, there are a number of data gaps. These gaps include data on lost batches, supply chains, data/communication errors, feedstocks, goods inventory, machinery maintenance, cyber security, developing new products, and in identifying biomanufactured goods. These data gaps might be filled with industry specific surveys.

References

[1] Allman, Tony. (2020). The Difference Between Batch, Fed-batch and Continuous Processes. https://www.infors-ht.com/en/blog/the-difference-between-batch-fed-batch-and-continuous-processes/ (Accessed 2/9/2023)
[2] Amato, D., Korhonen, J. (2021). Integrating the green economy, circular economy and bioeconomy in a strategic sustainability framework. Ecological Economics. Vol 188. https://doi.org/10.1016/j.ecolecon.2021.107143
[3] Ariely, Dan. (2008). Predictably Irrational: The Hidden Forces that Shape our Decisions. (New York, NY: Harper).
[4] Ashter, Syed Ali. (2016). 1 – Introduction. In Introduction to Bioplastics Engineering, William Andrew Publishing. Pages 1-17. https://doi.org/10.1016/B978-0-323-39396-6.00001-4.
[5] Bare, Jane. (2011). “TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts 2.0.” Clean Technologies and Environmental Policy. Vol 13 no. 5 (January 2011): 687-696.
[6] Bureau of Labor Statistics. 2022. Consumer Price Index. https://www.bls.gov/cpi/
[7] Burgman MA, McBride M, Ashton R, Speirs-Bridge A, Flander L, Wintle B, et al. (2011) Expert Status and Performance. PLoS ONE 6(7): e22998. https://doi.org/10.1371/journal.pone.0022998
[8] Cho, Renee. (2017). The Truth about Bioplastics. https://news.climate.columbia.edu/2017/12/13/the-truth-about-bioplastics/
[9] Chhajed, D. and T.J. Lowe (2008) Building Intuition: Insights from Basic Operations Management Models and Principles. New York, Springer.
[10] Clean Fuels Alliance. 2012. Biodiesel Basics. https://www.biodiesel.org/what-is-biodiesel/biodiesel-basics (Accessed 2/9/2023)
[11] Congressional Research Service. (2021). The Bioeconomy: A Primer. https://crsreports.congress.gov/product/pdf/R/R46881
[12] Connelly, Thomas et al. (2020). “Safeguarding the Bioeconomy.” National Academies Press. https://doi.org/10.17226/25525
[13] Daystar, J., Handfeld, R.B., Pascual-Gonzalez, J., McConnell, E. and J.S. Golden (2020). An Economic Impact Analysis of the U.S. Biobased Products Industry: 2019 Update. Volume IV. A Joint Publication of the Supply Chain Resource Cooperative at North Carolina State University and the College of Engineering and Technology at East Carolina University.
[14] Defusco, Richard, Dennis McLeavey, Jerald Pinto, and David Runkle (2015). Quantitative Investment Analysis. Hoboken, NJ: John Wiley and Sons. 54-56.
[15] Dornbusch, Rudiger, Stanley Fischer, and Richard Startz. (2000). Macroeconomics. 8th ed. London, UK: McGraw-Hill.
[16] Ekins, Paul; Domenech, Teresa; Drummond, Paul; Bleischwitz, Raimund; Hughes, Nick; Lotti, Lorenzo. (2019). The Circular Economy: What, Why, How and Where. https://www.oecd.org/cfe/regionaldevelopment/Ekins-2019-Circular-Economy-What-Why-How-Where.pdf
[17] EPA. (2016). Social Costs of Carbon. https://www.epa.gov/sites/default/files/2016-12/documents/social_cost_of_carbon_fact_sheet.pdf

[18] European Commission. (2022). Jobs and Wealth in the European Union Bioeconomy (Biomass producing and converting sectors). https://datam.jrc.ec.europa.eu/datam/mashup/BIOECONOMICS/index.html
[19] Harris, C. M. (1984). Issues in Sensitivity and Statistical Analysis of Large-Scale, Computer-Based Models, NBS GCR 84-466, Gaithersburg, MD: National Bureau of Standards.
[20] Homrich, Aline Sacchi; Galvae, Graziela; Abadia, Lorena Gamboa; Carvalho, Marly M. (2018). The Circular Economy Umbrella: Trends and Gaps on Integrating Pathways. Journal of Cleaner Production vol 175: 525-543. https://doi.org/10.1016/j.jclepro.2017.11.064
[21] Hopp,W.J. and M.L. Spearman (2008) Factory Physics. 3rd edition. Long Grove, IL,Waveland Press.
[22] Horngren, C.T., W.T. Harrison Jr. and L.S. Bamber (2002) Accounting. 5th edition. Upper Saddle River, NJ, Prentice Hall.
[23] Horowitz, Karen J. and Mark A. Planting. (2009). “Concepts and Methods of the U.S. Input-Output Accounts.” (2009): 1.5. http://www.bea.gov/papers/pdf/IOmanual_092906.pdf
[24] Industrial Assessment Center. (2021). Saving Energy and Reducing Costs at Small and Medium-sized U.S. Manufacturers. https://iac.university/#resources (accessed 10-25-2021).
[25] Jozala, Angela Faustino, Danilo Costa Geraldes, Louise Lacalendola Tundisi, Valker de Araújo Feitosa, Carlos Alexandre Breyer, Samuel Leite Cardoso, Priscila Gava Mazzola, Laura de Oliveira-Nascimento, Carlota de Oliveira Rangel-Yagui, Pérola de Oliveira Magalhães, Marcos Antonio de Oliveira, Adalberto Pessoa. (2016) Biopharmaceuticals from microorganisms: from production to purification, Brazilian Journal of Microbiology, Volume 47: 51-63. https://doi.org/10.1016/j.bjm.2016.10.007.
[26] Jurga, Piotr,, Efstratios Loizou, and Stelios Rozakis. (2021) Comparing Bioeconomy Potential at National vs. Regional Level Employing Input-Output Modeling. Energies, 14, 1714. https://doi.org/10.3390/en14061714
[27] Kahneman, Daniel. Thinking, Fast and Slow. 2011. (New York: Farrar, Straus, and Giroux).
[28] Kirchherr, Julian; Hekkert, Marko; Bour, Ruben; Huijbrechtse-Truijens, Anne; Kostense-Smit, Erica; Muller, Jennifer. (2017). "Breaking the Barriers to the Circular Economy." Deloitte. https://circulareconomy.europa.eu/platform/sites/default/files/171106_white_paper_breaking_the_barriers_to_the_circular_economy_white_paper_vweb-14021.pdf
[29] Koff, Jason. (2014). “Maximizing the Biodiesel Process.” https://www.tnstate.edu/extension/documents/MaximizingProduction.pdf
[30] Lippiatt, Barbara, Anne Landfield Greig, and Priya Lavappa. (2010). Building for Environmental and Economic Sustainability. National Institute of Standards and Technology. <http://www.nist.gov/el/economics/BEESSoftware.cfm>
[31] McKay, M. D., Conover, W. H. and Beckman, R.J.. (1979). “A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code,” Technometrics 21, (1979): 239-245.
[32] Mikulic, Matej. (2020). Biologics share of total pharmaceutical sales in select countries in 2018. Statista. https://www.statista.com/statistics/1118421/biologic-medicines-share-of-total-pharmaceutical-sales-in-oecd-countries
[33] Miller, Ronald E. and Peter D. Blair. (2009). Input-Output Analysis: Foundations and Extensions. (New York, NY: Cambridge University Press, 2009): 16.

[34] Meigs, R.F. and W.B. Meigs. (1993) Accounting: The Basis for Business Decisions. 9th edition. New York, McGraw-Hill Inc.
[35] NIST. (2012). Engineering Statistics Handbook. Sample Sizes. http://www.itl.nist.gov/div898/handbook/prc/section2/prc222.htm
[36] NIST. (2022). "NIST Bioeconomy Lexicon." https://www.nist.gov/bioscience/nist-bioeconomy-lexicon
[37] Oracle. (2013). "Crystal Ball." https://www.oracle.com/applications/crystalball/
[38] Ross, Stephen, Randolph Westerfield, and Jeffrey Jaffe. (2005) Corporate Finance. New York, NY: McGraw-Hill.
[39] Stickney, C.P. and P.R. Brown (1999) Financial Reporting and Statement Analysis. Mason, OH, Southwestern, 136-137.
[40] Svenson, Ola. 1981. "Are We All Less Risky and More Skillful Than Our Fellow Drivers?" Acta Psychologica. 47 (2): 143–148. doi:10.1016/0001-6918(81)90005-6
[41] Tetlock, Philip and Dan Gardner. 2015. Super Forecasting. Penguin Random House LLC, New York.
[42] Thomas, Douglas. (2017) Investment Analysis Methods: A practitioner's guide to understanding the basic principles for investment decisions in manufacturing. NIST Advanced Manufacturing Series 200-5. https://doi.org/10.6028/NIST.AMS.200-5
[43] Thomas, Douglas. (2018a) "An examination of national supply-chain flow time." Economic Systems Research. Vol 30 issue 3, 359-379. https://doi.org/10.1080/09535314.2017.1407296
[44] Thomas, Douglas. (2018b). "Life-Cycle Cost of Manufactured Goods: A Case Study in US Ground Passenger Transportation." 26th International Input-Output Conference. June 25-29, 2018, Juiz de Fora, Brazil. https://www.iioa.org/conferences/26th/papers/files/3165_20180130110_LCCofManufacturedGoods.pdf
[45] Thomas, Douglas. (2018c). "The Costs and Benefits of Advanced Maintenance in Manufacturing." NIST AMS 100-18. https://doi.org/10.6028/NIST.AMS.100-18
[46] Thomas, Douglas. (2019a) Manufacturing Cost Guide. https://www.nist.gov/services-resources/software/manufacturing-cost-guide
[47] Thomas, Douglas. (2019b) Reliability of using Periodic IO Data to Identify High Return Investments in Efficiency and Environmental Sustainability: An Examination of US Manufactured Tech Products. 27th International Input-Output Association Conference. Glasgow, Scottland. June 30th - July 5th. https://www.iioa.org/conferences/27th/papers/files/3747_20190128020_Thomas.pdf
[48] Thomas, Douglas. (2022) "Annual Report on U.S. Manufacturing Industry Statistics: 2022." NIST AMS 100-49. https://doi.org/10.6028/NIST.AMS.100-49
[49] Thomas, Douglas, Kandaswamy, Anand. (2019a) Identifying high resource consumption areas of assembly-centric manufacturing in the United States. J Technol Transf 44, 264-311. https://doi.org/10.1007/s10961-017-9577-9
[50] Thomas, Douglas, Kandaswamy, Anand. (2019b) Economic Guide for Identifying and Evaluating Industry Research Investments: A Focus on Applied Manufacturing Research. NIST Advanced Manufacturing Series 200-8. https://doi.org/10.6028/NIST.AMS.200-8
[51] Thomas, Douglas, Kandaswamy, Anand., and Kneifel, Joshua. (2017). Identifying High Resource Consumption Supply Chain Points: A Case Study in Automobile Production 25th International Input-Output Conference. June 19-23, 2017, Atlantic City, New Jersey, USA

[52] Thomas, Douglas. (2022). "Efficiency Improvements in U.S. Manufacturing Return on Investment for Small and Medium Establishments." NIST AMS 100-50. https://doi.org/10.6028/NIST.AMS.100-50
[53] U.S. Census Bureau. (2012). 2012 Quarterly Survey of Plant Capacity Utilization. https://www.census.gov/data/tables/2012/econ/qpc/qpc-quarterly-tables.html
[54] U.S. Census Bureau. (2021). Annual Survey of Manufactures. https://data.census.gov/table?n=N0600.00:N0600.31&tid=ASMAREA2017.AM1831BASIC01
[55] U.S. Department of Energy. 2011. IAC Assessment Database manual. Version 10.2. https://iac.university/technicalDocs/IAC_DatabaseManualv10.2.pdf
[56] U.S. Department of Energy 2013. "Diesel Vehicles Using Biodiesel." https://afdc.energy.gov/vehicles/diesel.html (Accessed 2/11/2023)
[57] U.S. Department of Energy. 2020. "Clean Cities Alternative Fuel Price Report." https://afdc.energy.gov/files/u/publication/alternative_fuel_price_report_july_2020.pdf
[58] U.S. Energy Information Administration. 2022. "State Energy Data 2020." https://www.eia.gov/state/seds/sep_prod/pdf/P1.pdf
[59] U.S. Environmental Protection Agency. (2018a). USEEIO Elementary Flows and Life Cycle Impact Assessment Characterization Factors. https://catalog.data.gov/dataset/useeio-elementary-flows-and-life-cycle-impact-assessment-lcia-characterization-factors
[60] U.S. Environmental Protection Agency. USEEIO v1.1. (2018b). https://catalog.data.gov/dataset/useeio-v1-1-matrices
[61] U.S. OSTP. 2012. National Bioeconomy Blueprint (USNBB). https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/national_bioeconomy_blueprint_april_2012.pdf
[62] U.S. OSTP. 2019. Summary of the 2019 White House summit on America's bioeconomy. https:// www.whitehouse.gov/wp-content/uploads/2019/10/Summary-of-White-HouseSummit-on-Americas-Bioeconomy-October-2019.pdf
[63] Van den Steen, Eric. 2004. "Rational Overoptimism (and Other Biases)." American Economic Review, 94 (4): 1141-1151. DOI: 10.1257/0002828042002697
[64] Wilson, T. D., Houston, C. E., Etling, K. M., & Brekke, N. (1996). A new look at anchoring effects: Basic anchoring and its antecedents. Journal of Experimental Psychology: General, 125(4), 387-402. http://dx.doi.org/10.1037/0096-3445.125.4.387
[65] Yang, Yi, Wesley W. Ingwersen, Troy R. Hawkins, Michael Srocka, David E. Meyer. (2017). "USEEIO: A New and Transparent United States Environmentally-Extended Input-Output Model." Journal of Cleaner Production. Vol 158, no. 1 (2017): 308-318. https://doi.org/10.1016/j.jclepro.2017.04.150

Appendix A. Data Used

A discussion on manufacturing cost data is presented in NIST AMS 100-18 (Thomas 2018c), Thomas (2019b), and Thomas and Kandaswamy (2019a). The following draws from these publications. The Manufacturing Cost Guide (i.e., Version 1.0), which is used for estimates in this report, estimates a number of values using 2012 economic input-output data. This data is released every 5 years and is delayed in its release due to the time required for assembly. The 2012 data, for instance, was released in the fall of 2018. The economy will have changed somewhat between 2012 and the present: however, these types of changes are relatively slow at the economy scale, as shown by Thomas (2019b).

Bureau of Economic Analysis Input-Output Data: Annual input-output data is available from the BEA for the years 1998 through 2016. Prior to 1998, the data is available for every fifth year starting in 1967. There is also data available for the years 1947, 1958, and 1963. More detailed data is available for years ending in two or seven. The input-output accounts provide data to analyze inter-industry relationships. BEA input-output data is provided in the form of make and use tables. Make tables show the production of commodities (products) by industry. Use tables show the components required for producing the output of each industry. There are two types of make and use tables: "standard" and "supplementary." Standard tables closely follow NAICS and are consistent with other economic accounts and industry statistics, which classify data based on establishment. Note that an "establishment" is a single physical location where business is conducted. This should not be confused with an "enterprise" such as a company, corporation, or institution. Establishments are classified into industries based on the primary activity within the NAICS code definitions. Establishments often have multiple activities. For example, a hotel with a restaurant has income from lodging (a primary activity) and from food sales (a secondary activity). An establishment is classified based on its primary activity. Data for an industry reflects all the products made by the establishments within that industry; therefore, secondary products are included. Supplementary make-use tables, which are used in the Manufacturing Cost Guide, reassign secondary products to the industry in which they are primary products (Horowitz et al. 2009).[6] The make-use tables are used for input-output analysis as developed by Leontief (Miller and Blair 2009; Horowitz et al. 2009).

Annual Survey of Manufactures and Economic Census: The Annual Survey of Manufactures (ASM) is conducted every year except for years ending in two or seven when the Economic Census is conducted. The ASM provides statistics on employment, payroll, supplemental labor costs, cost of materials consumed, operating expenses, value of shipments, value added, fuels and energy used, and inventories. It uses a sample survey of approximately 50 000 establishments with new samples selected at 5-year intervals. The ASM data allows the examination of multiple factors (value added, payroll, energy use, and more) of manufacturing at a detailed subsector level. The Economic Census, used for years ending in 2 or 7, is a survey of all employer establishments in the U.S. that has been taken as an integrated program at 5-year intervals since 1967. Both the ASM and the Economic Census use the NAICS codes; however, prior to NAICS the SIC system was used (U.S. Census Bureau 2021). NAICS and SIC are

[6] Over the years BEA has made improvements to its methods. This includes redefining secondary products. The data discussed in this section utilizes the data BEA refers to as "after redefinitions."

classifications of industries, which are based primarily on the product produced (e.g., automobiles, steel, or toys). The categories include both intermediate and finished goods.

Together, the ASM and the Economic Census provide annual data on manufacturing, including value added and capital. Value added is equal to the value of shipments less the cost of materials, supplies, containers, fuel, purchased electricity, and contract work. It is adjusted by the addition of value added by merchandising operations plus the net change in finished goods and work-in-process goods. Value added avoids the duplication caused from the use of products of some establishments as materials. It is important to note that the BEA, which is a prominent source of data on value added, and the ASM calculate value added differently. The BEA calculates value added as "gross output (sales or receipts and other operating income, plus inventory change) less intermediate inputs (consumption of goods and services purchased from other industries or imported)" (Horowitz 2009). Moreover, the difference is that ASM's calculation of value added includes purchases from other industries such as mining and construction while BEA's does not include it. Note that the BEA definition is followed for the Manufacturing Cost Guide, as the ASM's definition can result in double counting when adding data together.

Occupational Employment Statistics: The Occupational Employment Statistics program at the Bureau of Labor Statistics provides data on employment and wages for over 800 occupations categorized by the Standard Occupation Classification SOC) system and by NAICS code.

Manufacturing Energy Consumption Survey: The Energy Information Administration collects energy data on a quadrennial basis and samples approximately 15 500 establishments drawn from a nationally representative sample frame that includes 97 % to 98 % of the manufacturing payroll (Energy Information Administration 2010). Energy data is categorized by the NAICS codes and end use.

Environmentally Extended Input-Output Data: The environmental data used in this tool is the U.S. environmentally-extended input-output (USEEIO) data assembled by Yang et al (2017; U.S. Environmental Protection Agency 2018a; U.S. Environmental Protection Agency 2018b). This dataset provides the environmental impacts associated with the production of goods and services. A selection of the measures of impact were used in this analysis, which are consistent with metrics used by the U.S. Environmental Protection Agency's TRACI tool (Bare 2011).

Bureau of Labor Statistics: Industry values are adjusted to 2019 using the Consumer Price Index for all cities for all items from the Bureau of Labor Statistics (2022).

Appendix B. Economic Input-Output Analysis and Environmental Impact

A discussion on the methods for examining manufacturing costs is presented in NIST AMS 100-18, Thomas (2019), and Thomas and Kandaswamy (2017; Thomas 2018c; Thomas 2019b). The following is drawn from these publications.

Input-Output Analysis for BEA Data: The Manufacturing Cost Guide utilizes input-output analysis, which develops a total requirements matrix that when multiplied by a vector of final demands equals the output needed for production. The total requirements matrix is developed using the methods outlined in Horowitz and Planting (2009):

$$X = W(I - BW)^{-1} * Y \tag{B.1}$$

Where:
$X =$ Vector of output required to produce final demand
$Y =$ Vector of final demand, as defined in the BEA Input-Output data
$W = (I - \hat{p})D$
$B = U\hat{g}^{-1}$
$I =$ Identity matrix
$D = V\hat{q}^{-1}$
$p =$ "A column vector in which each entry shows the ratio of the value of scrap produced in each industry to the industry's total output."
$U =$ "Intermediate portion of the use matrix in which the column shows for a given industry the amount of each commodity it uses—including noncomparable imports, scrap, and used and secondhand goods. This is a commodity-by-industry matrix."
$V =$ "Make matrix, in which the column shows for a given commodity the amount produced in each industry. This is an industry-by-commodity matrix. V has columns showing only zero entries for noncomparable imports and for scrap."
$g =$ "A column vector in which each entry shows the total amount of each industry's output, including its production of scrap. It is an industry-by-one vector."
$q =$ "A column vector in which each entry shows the total amount of the output of a commodity. It is a commodity-by-one vector."
$\frown$ "A symbol that when placed over a vector indicates a square matrix in which the elements of the vector appear on the main diagonal and zeros elsewhere."

In Equation B.1, a total requirements matrix $W(I - BW)^{-1}$ is multiplied by a vector of final demand for commodities Y to estimate the total output X. The total requirements matrix provided by the BEA was used in this analysis. All variables in Equation B.1 have known values in the input-output data. The output X required to produce an alternate level of final demand can be calculated by altering the final demand vector from the actual final demand Y in the input output data to Y'. For the Manufacturing Cost Guide, Y' has the sum of the final demand and intermediate use for the commodities selected by the user. If the user selects multiple industries, the overlapping intermediate uses are subtracted from Y'.

Environmental Impact Categories: The TRACI 2 impact categories are each an aggregation of multiple emissions converted to a common physical unit. For example, the global warming impact category includes impacts of many pollutants, such as carbon dioxide (CO_2), methane (CH_4), Nitrous Oxide (NO_X), and fluorinated gases, which are converted to their carbon dioxide equivalent (CO_2e) impact and aggregated to estimate the total impact for that impact category. The environmental impacts are measured in terms of the common physical unit per dollar of output. The impact can be calculated by multiplying the output in the Input-Output analysis by the impact categories. One should note that when examining manufacturing activities, these impacts represent the environmental impact resulting from the production of goods and services within the economy. They do not include impacts due to consumer use and end-of-life waste streams.

Impact Category Weights: Having 12 impact categories makes it difficult to rank industry environmental activity; therefore, the 12 impact categories have been combined into one using the Analytical Hierarchy Process (AHP). AHP is a mathematical method for developing weights using normalized eigenvalues. It involves making pairwise comparisons of competing items. The weights used in this paper were developed for the BEES software and can be seen in Table 10.1 (Lippiatt 2010). This paper uses 12 of the 13 impact categories for which weights were developed. Indoor Air Quality (IAQ) is excluded because it is more applicable to the design of buildings and ventilation systems rather than to manufacturing activities. The weight of IAQ is proportionally allocated to the other 12 categories. The final metric for each industry or industry/commodity combination is the proportion of the total impact from assembly-centric products. The percent of environmental impacts, based on the weights, are calculated using the following equation:

(B.2)

$$\begin{aligned} Env_{z,Y'} = {} & \frac{x_{z,Y'} * GWP_z}{\sum_{i=1}^{n} x_{i,Y'} * GWP_i} * 0.30 + \frac{x_{z,Y'} * Acid_z}{\sum_{i=1}^{n} x_{i,Y'} * Acid_i} * 0.03 + \frac{x_{z,Y'} * HHA_z}{\sum_{i=1}^{n} x_{i,Y'} * HHA_i} * 0.09 \\ & + \frac{x_{z,Y'} * Eut_z}{\sum_{i=1}^{n} x_{i,Y'} * Eut_i} * 0.06 + \frac{x_{z,Y'} * OD_z}{\sum_{i=1}^{n} x_{i,Y'} * OD_i} * 0.02 + \frac{x_{z,Y'} * Sm_z}{\sum_{i=1}^{n} x_{i,Y'} * Sm_i} * 0.04 \\ & + \frac{x_{z,Y'} * Eco_z}{\sum_{i=1}^{n} x_{i,Y'} * Eco_i} * 0.07 + \frac{x_{z,Y'} * HHC_z}{\sum_{i=1}^{n} x_{i,Y'} * HHC_i} * 0.08 + \frac{x_{z,Y'} * HHNC_z}{\sum_{i=1}^{n} x_{i,Y'} * HHNC_i} \\ & * 0.05 + \frac{x_{z,Y'} * PE_z}{\sum_{i=1}^{n} x_{i,Y'} * PE_i} * 0.10 + \frac{x_{z,Y'} * LU_z}{\sum_{i=1}^{n} x_{i,Y'} * LU_i} * 0.06 + \frac{x_{z,Y'} * WC_z}{\sum_{i=1}^{n} x_{i,Y'} * WC_i} \\ & * 0.08 \end{aligned}$$

Where
$Env_{z,Y'}$ = Environmental impact from industry z for final demand Y'
GWP_z = Global warming potential per dollar of output for industry z
$Acid_z$ = Acidification per dollar of output for industry z
HHA_z = Human health –criteria air pollutants – per dollar of output for industry z
Eut_z = Eutrophication per dollar of output for industry z

OD_z = Ozone depletion per dollar of output for industry z
Sm_z = Smog per dollar of output for industry z
Eco_z = Ecotoxicity per dollar of output for industry z
HHC_z = Human health – carcinogens – per dollar of output for industry z
$HHNC_z$ = Human health – non-carcinogen – per dollar of output for industry z
PE_z = Primary energy consumption per dollar of output for industry z
LU_z = Land use per dollar of output for industry z
WC_z = Water consumption per dollar of output for industry z
$x_{z,Y'}$ = Output for industry z with final demand Y'

Value Added: The total requirements matrix $W(I - BW)^{-1}$ from Equation B.1, which shows the total output required to meet a given level of final demand, is multiplied by final demand in the input-output data to estimate the total output. As mentioned previously, the output required to produce a particular level of final demand can be calculated by altering final demand to Y'. For the Manufacturing Cost Guide, Y' equals the sum of final demand and intermediate uses for those NAICS codes (or ISIC codes) selected by the user. If the user selects multiple industries, the overlapping intermediate uses are subtracted from *Y'*.

Value added is calculated by assuming the proportion of output needed to produce a commodity is the same proportion of value added, which is consistent with methods proposed by Miller (2009). The proportions calculated using the input-output analysis are then multiplied by the value added:

$$VA_{z,Y',2012} = \frac{x_{z,Y',2012}}{x_{z,2012}} * VA_{z,2012} \tag{B.3}$$

Where
$VA_{z,Y',2012}$ = Value added from industry z with final demand Y' in 2012
$x_{z,2012}$ = Total output for industry z in 2012
$x_{z,Y',2012}$ = Output for industry z with final demand Y' in 2012
$VA_{z,2012}$ = Total value added from industry z in 2012

Imports in the "Supply Chain Analysis – Imports Oriented" option are calculated in a similar fashion, where the proportion of total output used from a particular industry is the same for imports. The ratio is multiplied by the intermediate imports from the BEA import matrix.

Labor: Due to data limitations, the labor data is aggregated to the 3-digit NAICS codes. Employment estimates by industry NAICS code by SOC occupation code are multiplied by the estimated hours worked per week in each industry. Note that this assumes that all occupations are working the average hours. The product of this is multiplied by the estimate of wages by industry NAICS code by SOC occupation code. The values are then scaled to match the BEA input-output data estimate of compensation. The result is then multiplied by the proportion of the ratio of $x_{z,Y',2012}$ to $x_{z,2012}$, which is consistent with methods proposed in Miller (2009). The result is a matrix of the compensation of labor, categorized by NAICS by SOC, to produce the selected commodities:

$$C_{z,s,Y'} = \frac{x_{z,Y'}}{x_z} * C_{z,s,} * \left(\frac{E_{z,s} * LH_s * W_{z,s}}{\sum_{i=1}^{n} E_{z,i} * LH_s * W_{z,i}}\right) \tag{B.4}$$

Where
$C_{z,s,Y'}$ = Compensation for occupation s in industry z with final demand Y'
$C_{z,s,}$ = Total compensation for occupation s in industry z
x_z = Total output for industry z
$x_{z,Y'}$ = Output for industry z with final demand Y'
$E_{z,s}$ = Employment for industry z and occupation s
LH_s = Labor hours per employee for occupation s
$W_{z,s}$ = Hourly wages per employee for industry z and occupation s

Adjusting for Inflation: Values are adjusted to 2019 using the Consumer Price Index for all cities for all items from the Bureau of Labor Statistics.[7]

Table 10.1: Environmental Impact Categories and Weights for Assessing Impact

Items to be measured	Units	Weights
Global Warming Potential	kg CO_2 eq	0.30
Acidification	H^+ moles eq	0.03
Human Health- Criteria Air Pollutants	kg PM_{10} eq	0.09
Eutrophication	kg N eq	0.06
Ozone Depletion	kg CFC-11 eq	0.02
Smog	kg O_3 eq	0.04
Ecotoxicity	CTUe	0.07
Human Health - Carcinogens	CTUHcan	0.08
Human Health – Non- Carcinogens	CTUHnoncan	0.05
Primary Energy Consumption	thousand BTU	0.10
Land Use	acre	0.06
Water Consumption	kg	0.08

[7] Bureau of Labor Statistics. Consumer Price Index. https://www.bls.gov/cpi/

Appendix C. Food, Beverage, and Tobacco Manufacturing Supply Chain (NAICS 311, 312)

Note: Environmental impacts are calculated using methods described in Appendix B. Calculated as a percent of total environmental impact resulting from economic activity in all U.S. industries.

		A	B	A+B	(100*B)/(A+B)	C
Code	Industry Description	Value Added ($million 2019)	Imports ($million 2019)	Total ($million 2019)	Percent Imported	Environmental Impact (1/1000th of a percent of Total U.S.)
424A00	Other nondurable goods merchant wholesalers	35 288.6	828.2	36 116.8	2.3%	0.037
1121A0	Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	31 892.6	2 286.1	34 178.7	6.7%	53.125
1111B0	Grain farming	21 086.2	7 146.7	28 232.9	25.3%	85.761
424400	Grocery and related product wholesalers	25 334.7	832.0	26 166.6	3.2%	0.028
112A00	Animal production, except cattle and poultry and eggs	24 620.6	520.7	25 141.3	2.1%	12.196
550000	Management of companies and enterprises	23 670.9	819.6	24 490.5	3.3%	0.017
324110	Petroleum refineries	7 173.6	17 267.2	24 440.8	70.6%	0.995
211000	Oil and gas extraction	21 193.3	2 003.1	23 196.5	8.6%	9.365
1111A0	Oilseed farming	21 287.7	1 711.7	22 999.4	7.4%	32.884
531ORE	Other real estate	21 907.8	644.2	22 551.9	2.9%	0.112
484000	Truck transportation	21 003.5	1 038.8	22 042.2	4.7%	10.747
221100	Electric power generation, transmission, and distribution	12 598.9	972.8	13 571.7	7.2%	10.806
111300	Fruit and tree nut farming	12 807.3	467.7	13 275.0	3.5%	10.051
115000	Support activities for agriculture and forestry	11 600.9	755.6	12 356.5	6.1%	1.343
112120	Dairy cattle and milk production	9 705.4	2 415.0	12 120.4	19.9%	11.311
52A000	Monetary authorities and depository credit intermediation	9 402.3	134.3	9 536.6	1.4%	0.001
325190	Other basic organic chemical manufacturing	6 482.5	2 528.9	9 011.4	28.1%	1.545
325310	Fertilizer manufacturing	6 419.6	1 981.0	8 400.7	23.6%	1.636
482000	Rail transportation	7 322.6	766.7	8 089.3	9.5%	1.566
322210	Paperboard container manufacturing	5 126.3	1 958.2	7 084.4	27.6%	0.272
423A00	Other durable goods merchant wholesalers	6 304.8	191.8	6 496.6	3.0%	0.007
111900	Other crop farming	5 627.7	814.7	6 442.4	12.6%	19.873
424700	Petroleum and petroleum products	6 339.6	81.0	6 420.6	1.3%	0.005
561300	Employment services	6 223.9	61.6	6 285.5	1.0%	0.001
425000	Wholesale electronic markets and agents and brokers	6 067.9	122.4	6 190.3	2.0%	0.004
522A00	Nondepository credit intermediation and related activities	6 044.8	97.5	6 142.3	1.6%	0.006
5241XX	Insurance carriers, except direct life	4 749.4	1 045.7	5 795.1	18.0%	0.001
541300	Architectural, engineering, and related services	5 455.0	243.0	5 698.0	4.3%	0.002
114000	Fishing, hunting and trapping	5 135.7	362.6	5 498.3	6.6%	0.069
325110	Petrochemical manufacturing	4 359.5	1 070.9	5 430.4	19.7%	0.286
561700	Services to buildings and dwellings	5 038.1	351.4	5 389.6	6.5%	0.001
541100	Legal services	5 262.3	63.7	5 326.0	1.2%	0.001

541200	Accounting, tax preparation, bookkeeping, and payroll services	5 191.1	62.6	5 253.6	1.2%	0.001
332430	Metal can, box, and other metal container (light gauge) manufacturing	3 615.7	1 542.3	5 157.9	29.9%	0.002
533000	Lessors of nonfinancial intangible assets	5 056.1	62.5	5 118.6	1.2%	0.001
33131B	Aluminum product manufacturing from purchased aluminum	2 570.9	2 364.1	4 935.0	47.9%	0.096
423800	Machinery, equipment, and supplies	4 808.4	111.4	4 919.8	2.3%	0.005
524200	Insurance agencies, brokerages, and related activities	4 726.9	31.9	4 758.8	0.7%	0.001
230301	Nonresidential maintenance and repair	4 256.8	452.6	4 709.4	9.6%	0.227
112300	Poultry and egg production	3 839.7	641.2	4 480.9	14.3%	3.349
325320	Pesticide and other agricultural chemical manufacturing	3 016.4	1 413.0	4 429.4	31.9%	0.215
48A000	Scenic and sightseeing transportation and support activities for transportation	4 012.6	255.3	4 267.9	6.0%	0.000
326160	Plastics bottle manufacturing	2 790.8	1 398.0	4 188.8	33.4%	0.019
325211	Plastics material and resin manufacturing	2 393.5	1 525.7	3 919.3	38.9%	0.366
221200	Natural gas distribution	3 748.5	157.3	3 905.9	4.0%	0.742
541610	Management consulting services	3 593.6	90.0	3 683.6	2.4%	0.001
5419A0	All other miscellaneous professional, scientific, and technical services	3 507.0	137.8	3 644.8	3.8%	0.001
S00203	Other state and local government enterprises	3 345.9	162.9	3 508.8	4.6%	0.291
532400	Commercial and industrial machinery and equipment rental and leasing	3 324.9	78.6	3 403.4	2.3%	0.002
811100	Automotive repair and maintenance	3 084.9	245.3	3 330.2	7.4%	0.009
541800	Advertising, public relations, and related services	3 186.1	91.9	3 278.0	2.8%	0.004
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	2 378.2	890.4	3 268.6	27.2%	0.048
327200	Glass and glass product manufacturing	2 814.3	417.3	3 231.6	12.9%	0.002
811300	Commercial and industrial machinery and equipment repair and maintenance	2 951.3	249.9	3 201.1	7.8%	0.007
326190	Other plastics product manufacturing	2 496.7	679.1	3 175.8	21.4%	0.103
334413	Semiconductor and related device manufacturing	2 938.4	194.5	3 132.9	6.2%	0.002
322130	Paperboard mills	2 341.6	776.2	3 117.9	24.9%	0.908
331110	Iron and steel mills and ferroalloy manufacturing	1 576.9	1 144.9	2 721.9	42.1%	0.002
541512	Computer systems design services	2 592.0	78.4	2 670.5	2.9%	0.002
322120	Paper mills	1 788.7	696.8	2 485.5	28.0%	0.652
322220	Paper Bag and Coated and Treated Paper Manufacturing	1 824.1	618.6	2 442.7	25.3%	0.099
562000	Waste management and remediation services	2 190.2	218.4	2 408.6	9.1%	0.503
212100	Coal mining	2 118.1	278.7	2 396.7	11.6%	2.472
492000	Couriers and messengers	2 250.4	131.5	2 382.0	5.5%	0.012
325180	Other Basic Inorganic Chemical Manufacturing	1 899.7	458.1	2 357.8	19.4%	0.415
481000	Air transportation	1 821.6	465.3	2 286.9	20.3%	0.156
493000	Warehousing and storage	2 094.9	122.1	2 217.0	5.5%	0.010
517110	Wired telecommunications carriers	2 041.7	170.9	2 212.6	7.7%	0.001
332710	Machine shops	1 959.1	208.7	2 167.7	9.6%	0.002
3259A0	All other chemical product and preparation manufacturing	1 501.1	664.4	2 165.4	30.7%	0.096
523A00	Securities and commodity contracts intermediation and brokerage	1 703.8	306.0	2 009.8	15.2%	0.001

Appendix D. Leather Supply Chain (NAICS 316)

Note: Environmental impacts are calculated using methods described in Appendix B. Calculated as a percent of total environmental impact resulting from economic activity in all U.S. industries.

		A	B	A+B	(100*B)/(A+B)	C
Code	Industry Description	Value Added ($million 2019)	Imports ($million 2019)	Total ($million 2019)	Percent Imported	Environmental Impact (1/1000th of a percent of Total U.S.)
424A00	Other nondurable goods merchant wholesalers	457.8	10.7	468.6	2.3%	0.000
1121A0	Beef cattle ranching and farming, including feedlots and dual-purpose ranching and farming	217.4	15.6	232.9	6.7%	0.362
550000	Management of companies and enterprises	202.4	7.0	209.4	3.3%	0.000
31161A	Animal (except poultry) slaughtering, rendering, and processing	156.9	41.4	198.3	20.9%	0.004
112A00	Animal production, except cattle and poultry and eggs	163.3	3.5	166.8	2.1%	0.081
423400	Professional and commercial equipment and supplies	149.1	2.6	151.6	1.7%	0.000
324110	Petroleum refineries	36.0	86.7	122.7	70.6%	0.005
211000	Oil and gas extraction	105.0	9.9	114.9	8.6%	0.046
531ORE	Other real estate	104.5	3.1	107.6	2.9%	0.001
484000	Truck transportation	97.7	4.8	102.5	4.7%	0.050
541300	Architectural, engineering, and related services	80.4	3.6	84.0	4.3%	0.000
52A000	Monetary authorities and depository credit intermediation	77.1	1.1	78.2	1.4%	0.000
423A00	Other durable goods merchant wholesalers	73.6	2.2	75.9	3.0%	0.000
524200	Insurance agencies, brokerages, and related activities	75.2	0.5	75.7	0.7%	0.000
221100	Electric power generation, transmission, and distribution	67.6	5.2	72.8	7.2%	0.058
424700	Petroleum and petroleum products	69.9	0.9	70.7	1.3%	0.000
325610	Soap and cleaning compound manufacturing	59.6	10.2	69.9	14.6%	0.002
313200	Fabric mills	52.7	13.7	66.5	20.7%	0.001
522A00	Nondepository credit intermediation and related activities	64.4	1.0	65.5	1.6%	0.000
313300	Textile and fabric finishing and fabric coating mills	40.9	18.7	59.6	31.4%	0.002
533000	Lessors of nonfinancial intangible assets	56.9	0.7	57.6	1.2%	0.000
561300	Employment services	56.0	0.6	56.6	1.0%	0.000

424400	Grocery and related product wholesalers	52.6	1.7	54.3	3.2%	0.000
5241XX	Insurance carriers, except direct life	38.8	8.5	47.3	18.0%	0.000
541200	Accounting, tax preparation, bookkeeping, and payroll services	46.2	0.6	46.8	1.2%	0.000
541100	Legal services	45.0	0.5	45.6	1.2%	0.000
541800	Advertising, public relations, and related services	44.3	1.3	45.5	2.8%	0.000
325211	Plastics material and resin manufacturing	26.8	17.1	43.9	38.9%	0.004
1111B0	Grain farming	32.0	10.9	42.9	25.3%	0.130
334413	Semiconductor and related device manufacturing	39.7	2.6	42.3	6.2%	0.000
5419A0	All other miscellaneous professional, scientific, and technical services	39.2	1.5	40.8	3.8%	0.000
423800	Machinery, equipment, and supplies	37.7	0.9	38.5	2.3%	0.000
325110	Petrochemical manufacturing	29.9	7.3	37.2	19.7%	0.002
541610	Management consulting services	34.8	0.9	35.7	2.4%	0.000
325190	Other basic organic chemical manufacturing	24.5	9.6	34.1	28.1%	0.006
561700	Services to buildings and dwellings	31.8	2.2	34.0	6.5%	0.000
425000	Wholesale electronic markets and agents and brokers	32.0	0.6	32.6	2.0%	0.000
541512	Computer systems design services	30.3	0.9	31.2	2.9%	0.000
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	18.8	7.0	25.8	27.2%	0.000
493000	Warehousing and storage	24.1	1.4	25.5	5.5%	0.000
48A000	Scenic and sightseeing transportation and support activities for transportation	22.4	1.4	23.8	6.0%	0.003
115000	Support activities for agriculture and forestry	22.3	1.5	23.7	6.1%	0.003
332710	Machine shops	21.1	2.2	23.4	9.6%	0.000
423600	Household appliances and electrical and electronic goods	22.2	0.5	22.7	2.4%	0.000
230301	Nonresidential maintenance and repair	20.2	2.1	22.4	9.6%	0.001
326190	Other plastics product manufacturing	17.4	4.7	22.1	21.4%	0.001
811300	Commercial and industrial machinery and equipment repair and maintenance	20.1	1.7	21.8	7.8%	0.000
481000	Air transportation	17.2	4.4	21.6	20.3%	0.001
339910	Jewelry and silverware manufacturing	12.0	9.3	21.3	43.6%	0.000
332800	Coating, engraving, heat treating and allied activities	18.0	3.2	21.2	15.0%	0.000
326290	Other rubber product manufacturing	14.0	6.6	20.6	32.2%	0.000
482000	Rail transportation	18.2	1.9	20.1	9.5%	0.004
518200	Data processing, hosting, and related services	18.6	1.4	20.0	6.9%	0.000
517110	Wired telecommunications carriers	18.3	1.5	19.8	7.7%	0.000
424200	Drugs and druggists’ sundries	18.6	0.4	19.0	2.1%	0.000
492000	Couriers and messengers	17.8	1.0	18.8	5.5%	0.000
811100	Automotive repair and maintenance	16.6	1.3	17.9	7.4%	0.000
311119	Other animal food manufacturing	12.5	5.1	17.7	29.0%	0.001
515100	Radio and television broadcasting	17.4	0.1	17.5	0.8%	0.000

523A00	Securities and commodity contracts intermediation and brokerage	14.8	2.7	17.5	15.2%	0.000
532400	Commercial and industrial machinery and equipment rental and leasing	17.0	0.4	17.4	2.3%	0.000
3252A0	Synthetic rubber and artificial and synthetic fibers and filaments manufacturing	11.6	5.8	17.4	33.3%	0.008
561400	Business support services	16.6	0.7	17.4	4.1%	0.000
339990	All other miscellaneous manufacturing	14.6	2.3	17.0	13.8%	0.000
517210	Wireless telecommunications carriers (except satellite)	14.8	2.1	16.9	12.2%	0.000
322210	Paperboard container manufacturing	12.2	4.7	16.9	27.6%	0.001
1111A0	Oilseed farming	15.3	1.2	16.6	7.4%	0.024
519130	Internet publishing and broadcasting and Web search portals	15.7	0.7	16.4	4.6%	0.000
S00203	Other state and local government enterprises	15.5	0.8	16.3	4.6%	0.001
325180	Other Basic Inorganic Chemical Manufacturing	12.8	3.1	15.9	19.4%	0.003
323110	Printing	13.9	1.7	15.5	10.7%	0.000

Appendix E. Paper and Wood Product Supply Chain (NAICS 321, 322)

Note: Environmental impacts are calculated using methods described in Appendix B. Calculated as a percent of total environmental impact resulting from economic activity in all U.S. industries.

	A	B	A+B	(100*B)/(A+B)	C
Industry Description	Value Added ($million 2019)	Imports ($million 2019)	Total ($million 2019)	Percent Imported	Environmental Impact (1/1000th of a percent of Total U.S.)
Paper mills	16 717.4	6 511.9	23 229.3	28.0%	0.006
Paperboard container manufacturing	13 671.7	5 222.4	18 894.1	27.6%	0.001
Paperboard mills	9 551.2	3 166.1	12 717.3	24.9%	0.004
Sawmills and wood preservation	8 290.8	1 495.2	9 786.0	15.3%	0.002
Millwork	7 382.7	2 179.0	9 561.7	22.8%	0.000
All other wood product manufacturing	6 791.9	2 222.1	9 014.0	24.7%	0.000
Forestry and logging	8 358.7	131.9	8 490.7	1.6%	0.014
Paper Bag and Coated and Treated Paper Manufacturing	6 235.7	2 114.7	8 350.3	25.3%	0.000
Veneer, plywood, and engineered wood product manufacturing	6 499.6	1 491.7	7 991.3	18.7%	0.002
Other durable goods merchant wholesalers	7 612.5	231.6	7 844.1	3.0%	0.000
Petroleum refineries	2 093.0	5 037.9	7 130.9	70.6%	0.000
Oil and gas extraction	6 380.8	603.1	6 983.9	8.6%	0.003
Sanitary paper product manufacturing	4 676.5	1 317.4	5 993.9	22.0%	0.001
Electric power generation, transmission, and distribution	5 514.8	425.8	5 940.6	7.2%	0.005
Management of companies and enterprises	5 199.1	180.0	5 379.1	3.3%	0.000
Other nondurable goods merchant wholesalers	5 174.3	121.4	5 295.8	2.3%	0.000
Truck transportation	3 371.7	166.8	3 538.4	4.7%	0.002
Other real estate	2 830.6	83.2	2 913.8	2.9%	0.000
Other Basic Inorganic Chemical Manufacturing	2 282.4	550.4	2 832.8	19.4%	0.000
Rail transportation	2 429.3	254.4	2 683.7	9.5%	0.001
Support activities for agriculture and forestry	2 402.4	156.5	2 558.8	6.1%	0.000
Pulp mills	1 885.5	595.0	2 480.5	24.0%	0.002
Stationery product manufacturing	1 782.7	667.2	2 449.9	27.2%	0.000
Other basic organic chemical manufacturing	1 638.7	639.3	2 278.0	28.1%	0.000
Architectural, engineering, and related services	2 016.6	89.8	2 106.4	4.3%	0.000
Plastics material and resin manufacturing	1 283.6	818.2	2 101.9	38.9%	0.000
Petrochemical manufacturing	1 633.3	401.2	2 034.5	19.7%	0.000
All other converted paper product manufacturing	1 592.8	417.6	2 010.4	20.8%	0.000
Monetary authorities and depository credit intermediation	1 745.1	24.9	1 770.0	1.4%	0.000
Machine shops	1 582.6	168.6	1 751.2	9.6%	0.000
Adhesive manufacturing	1 214.0	532.2	1 746.1	30.5%	0.000
Services to buildings and dwellings	1 592.7	111.1	1 703.8	6.5%	0.000
Employment services	1 685.9	16.7	1 702.5	1.0%	0.000
Plastics packaging materials and unlaminated film and sheet manufacturing	1 207.7	452.2	1 659.9	27.2%	0.000
Petroleum and petroleum products	1 573.7	20.1	1 593.8	1.3%	0.000

Legal services	1 519.8	18.4	1 538.2	1.2%	0.000
Nondepository credit intermediation and related activities	1 509.5	24.3	1 533.9	1.6%	0.000
Scenic and sightseeing transportation and support activities for transportation	1 396.6	88.8	1 485.5	6.0%	0.000
Coating, engraving, heat treating and allied activities	1 243.7	219.5	1 463.2	15.0%	0.000
Accounting, tax preparation, bookkeeping, and payroll services	1 412.1	17.0	1 429.1	1.2%	0.000
Natural gas distribution	1 312.4	55.1	1 367.5	4.0%	0.000
Commercial and industrial machinery and equipment repair and maintenance	1 159.3	98.1	1 257.5	7.8%	0.000
Lessors of nonfinancial intangible assets	1 236.2	15.3	1 251.5	1.2%	0.000
Nonresidential maintenance and repair	1 105.8	117.6	1 223.3	9.6%	0.000
Fabric mills	955.5	248.9	1 204.4	20.7%	0.000
Coal mining	1 053.7	138.6	1 192.4	11.6%	0.001
Iron and steel mills and ferroalloy manufacturing	674.3	489.6	1 163.8	42.1%	0.000
Professional and commercial equipment and supplies	1 122.6	19.3	1 141.9	1.7%	0.000
Machinery, equipment, and supplies	1 097.8	25.4	1 123.2	2.3%	0.000
Semiconductor and related device manufacturing	1 028.0	68.0	1 096.0	6.2%	0.000
Management consulting services	952.6	23.9	976.5	2.4%	0.000
Automotive repair and maintenance	884.8	70.3	955.1	7.4%	0.000
Insurance carriers, except direct life	762.9	168.0	930.8	18.0%	0.000
Insurance agencies, brokerages, and related activities	889.4	6.0	895.4	0.7%	0.000
State and local government other services	852.1	37.9	890.0	4.3%	0.000
Wholesale electronic markets and agents and brokers	869.5	17.5	887.0	2.0%	0.000
Other state and local government enterprises	803.4	39.1	842.6	4.6%	0.000
Computer systems design services	787.6	23.8	811.4	2.9%	0.000
Advertising, public relations, and related services	756.4	21.8	778.2	2.8%	0.000
Commercial and industrial machinery and equipment rental and leasing	754.7	17.8	772.5	2.3%	0.000
Other crop farming	674.0	97.6	771.6	12.6%	0.002
All other chemical product and preparation manufacturing	528.5	233.9	762.4	30.7%	0.000
Printing	675.6	81.3	756.9	10.7%	0.000
Other Motor Vehicle Parts Manufacturing	452.5	293.2	745.7	39.3%	0.000
State and local government electric utilities	684.6	59.1	743.7	7.9%	0.001
Waste management and remediation services	656.6	65.5	722.1	9.1%	0.000
All other miscellaneous professional, scientific, and technical services	690.2	27.1	717.3	3.8%	0.000
Other plastics product manufacturing	531.6	144.6	676.2	21.4%	0.000
Air transportation	537.7	137.3	675.0	20.3%	0.000
Synthetic dye and pigment manufacturing	504.5	166.6	671.1	24.8%	0.000
Wired telecommunications carriers	616.3	51.6	667.9	7.7%	0.000

Appendix F. Other Basic Organic Chemical Manufacturing Supply Chain (NAICS 325190)

Note: Environmental impacts are calculated using methods described in Appendix B. Calculated as a percent of total environmental impact resulting from economic activity in all U.S. industries.

		A	B	A+B	(100*B)/(A+B)	C
Code	Industry Description	Value Added ($million 2019)	Imports ($million 2019)	Total ($million 2019)	Percent Imported	Environmental Impact (1/1000th of a percent of Total U.S.)
211000	Oil and gas extraction	17 591.8	1 662.7	19 254.6	8.6%	7.773
325110	Petrochemical manufacturing	13 705.1	3 366.7	17 071.9	19.7%	0.899
424A00	Other nondurable goods merchant wholesalers	6 045.5	141.9	6 187.4	2.3%	0.006
324110	Petroleum refineries	5 867.2	14 122.6	19 989.7	70.6%	0.814
1111B0	Grain farming	5 194.6	1 760.6	6 955.3	25.3%	21.127
550000	Management of companies and enterprises	3 036.7	105.1	3 141.9	3.3%	0.002
531ORE	Other real estate	2 889.3	85.0	2 974.3	2.9%	0.015
221100	Electric power generation, transmission, and distribution	2 752.2	212.5	2 964.6	7.2%	2.360
484000	Truck transportation	2 131.3	105.4	2 236.7	4.7%	1.091
424700	Petroleum and petroleum products	1 881.5	24.0	1 905.6	1.3%	0.001
325310	Fertilizer manufacturing	1 858.9	573.6	2 432.5	23.6%	0.474
325180	Other Basic Inorganic Chemical Manufacturing	1 811.9	436.9	2 248.8	19.4%	0.396
115000	Support activities for agriculture and forestry	1 577.6	102.7	1 680.3	6.1%	0.183
482000	Rail transportation	1 472.5	154.2	1 626.7	9.5%	0.315
221200	Natural gas distribution	1 385.0	58.1	1 443.2	4.0%	0.274
52A000	Monetary authorities and depository credit intermediation	1 283.3	18.3	1 301.6	1.4%	0.000
325211	Plastics material and resin manufacturing	1 193.4	760.7	1 954.1	38.9%	0.182
541300	Architectural, engineering, and related services	1 145.6	51.0	1 196.6	4.3%	0.000
423A00	Other durable goods merchant wholesalers	1 099.2	33.4	1 132.6	3.0%	0.001
561700	Services to buildings and dwellings	1 062.7	74.1	1 136.8	6.5%	0.003
S00203	Other state and local government enterprises	1 053.0	51.3	1 104.3	4.6%	0.092
533000	Lessors of nonfinancial intangible assets	1 052.8	13.0	1 065.8	1.2%	0.000
230301	Nonresidential maintenance and repair	1 005.1	106.9	1 112.0	9.6%	0.041
486000	Pipeline transportation	960.9	11.9	972.8	1.2%	0.595
1111A0	Oilseed farming	940.3	75.6	1 015.9	7.4%	1.452
562000	Waste management and remediation services	916.3	91.4	1 007.7	9.1%	0.210
561300	Employment services	904.3	8.9	913.2	1.0%	0.000
541100	Legal services	870.7	10.5	881.3	1.2%	0.000
522A00	Nondepository credit intermediation and related activities	811.6	13.1	824.7	1.6%	0.001
21311A	Other support activities for mining	806.3	40.7	847.1	4.8%	0.023
5241XX	Insurance carriers, except direct life	700.7	154.3	855.0	18.0%	0.000
541200	Accounting, tax preparation, bookkeeping, and payroll services	687.9	8.3	696.2	1.2%	0.000
811300	Commercial and industrial machinery and equipment repair and maintenance	669.7	56.7	726.4	7.8%	0.002

532400	Commercial and industrial machinery and equipment rental and leasing	667.8	15.8	683.5	2.3%	0.000
541610	Management consulting services	641.9	16.1	658.0	2.4%	0.000
3259A0	All other chemical product and preparation manufacturing	569.9	252.3	822.2	30.7%	0.036
334413	Semiconductor and related device manufacturing	549.6	36.4	586.0	6.2%	0.004
423800	Machinery, equipment, and supplies	545.5	12.6	558.1	2.3%	0.001
811100	Automotive repair and maintenance	524.1	41.7	565.7	7.4%	0.002
524200	Insurance agencies, brokerages, and related activities	519.8	3.5	523.3	0.7%	0.000
311221	Wet corn milling	515.1	62.5	577.6	10.8%	0.208
48A000	Scenic and sightseeing transportation and support activities for transportation	512.3	32.6	544.8	6.0%	0.064
5419A0	All other miscellaneous professional, scientific, and technical services	449.3	17.7	466.9	3.8%	0.000
325320	Pesticide and other agricultural chemical manufacturing	443.0	207.5	650.5	31.9%	0.032
425000	Wholesale electronic markets and agents and brokers	427.5	8.6	436.1	2.0%	0.000
326120	Plastics pipe, pipe fitting, and unlaminated profile shape manufacturing	406.4	111.7	518.1	21.6%	0.035
424400	Grocery and related product wholesalers	396.8	13.0	409.9	3.2%	0.000
541512	Computer systems design services	395.3	12.0	407.3	2.9%	0.000
454000	Nonstore retailers	389.6	11.5	401.1	2.9%	0.000
541800	Advertising, public relations, and related services	380.1	11.0	391.0	2.8%	0.000
2123A0	Other nonmetallic mineral mining and quarrying	373.2	53.5	426.7	12.5%	0.080
111400	Greenhouse, nursery, and floriculture production	364.3	30.3	394.6	7.7%	0.056
324190	Other petroleum and coal products manufacturing	353.0	101.5	454.4	22.3%	0.031
212100	Coal mining	340.1	44.7	384.8	11.6%	0.397
GSLGO	State and local government other services	337.4	15.0	352.4	4.3%	0.002
S00202	State and local government electric utilities	332.6	28.7	361.3	7.9%	0.377
33291A	Valve and fittings other than plumbing	322.2	72.0	394.3	18.3%	0.001
113000	Forestry and logging	315.1	5.0	320.0	1.6%	0.546
517110	Wired telecommunications carriers	314.1	26.3	340.4	7.7%	0.000
334514	Totalizing fluid meter and counting device manufacturing	303.3	20.1	323.4	6.2%	0.000
325610	Soap and cleaning compound manufacturing	293.3	50.2	343.5	14.6%	0.010
332710	Machine shops	289.5	30.8	320.4	9.6%	0.001
481000	Air transportation	286.6	73.2	359.7	20.3%	0.025
331110	Iron and steel mills and ferroalloy manufacturing	285.7	207.4	493.1	42.1%	0.076
423600	Household appliances and electrical and electronic goods	283.9	7.0	290.9	2.4%	0.000
111900	Other crop farming	276.1	40.0	316.0	12.6%	0.975
561400	Business support services	273.3	11.7	285.0	4.1%	0.000
492000	Couriers and messengers	257.7	15.1	272.7	5.5%	0.001
491000	Postal service	251.3	9.3	260.7	3.6%	0.001
332800	Coating, engraving, heat treating and allied activities	250.4	44.2	294.6	15.0%	0.005
493000	Warehousing and storage	249.9	14.6	264.4	5.5%	0.001

Appendix G. Select Pharmaceutical/Medicine Manufacturing Supply Chain (NAICS 325411, 325414)

Note: Environmental impacts are calculated using methods described in Appendix B. Calculated as a percent of total environmental impact resulting from economic activity in all U.S. industries.

		A	B	A+B	(100*B)/(A+B)	C
Code	Industry Description	Value Added ($million 2019)	Imports ($million 2019)	Total ($million 2019)	Percent Imported	Environmental Impact (1/1 000 000th of a percent of Total U.S.)
424200	Drugs and druggists' sundries	2 368.1	49.9	2 418.0	2.1%	0.492
325412	Pharmaceutical preparation manufacturing	1 048.5	90.0	1 138.5	7.9%	0.581
325413	In-vitro diagnostic substance manufacturing	728.7	154.1	882.8	17.5%	0.715
550000	Management of companies and enterprises	639.9	22.2	662.0	3.3%	61.239
325190	Other basic organic chemical manufacturing	277.7	108.3	386.0	28.1%	1.481
324110	Petroleum refineries	110.8	266.6	377.3	70.6%	16.484
211000	Oil and gas extraction	334.5	31.6	366.1	8.6%	0.146
221100	Electric power generation, transmission, and distribution	224.4	17.3	241.7	7.2%	4.036
424A00	Other nondurable goods merchant wholesalers	225.4	5.3	230.6	2.3%	12.226
531ORE	Other real estate	208.8	6.1	214.9	2.9%	0.010
524200	Insurance agencies, brokerages, and related activities	189.7	1.3	191.0	0.7%	2.455
325110	Petrochemical manufacturing	151.9	37.3	189.2	19.7%	147.803
5241XX	Insurance carriers, except direct life	152.1	33.5	185.6	18.0%	18.131
52A000	Monetary authorities and depository credit intermediation	179.5	2.6	182.1	1.4%	0.386
541800	Advertising, public relations, and related services	163.9	4.7	168.6	2.8%	0.552
484000	Truck transportation	138.5	6.8	145.4	4.7%	0.301
522A00	Nondepository credit intermediation and related activities	134.9	2.2	137.1	1.6%	1.296
561300	Employment services	116.6	1.2	117.7	1.0%	0.001
541300	Architectural, engineering, and related services	108.1	4.8	112.9	4.3%	0.446
533000	Lessors of nonfinancial intangible assets	99.8	1.2	101.1	1.2%	192.451
541100	Legal services	95.7	1.2	96.9	1.2%	6.979
561700	Services to buildings and dwellings	88.0	6.1	94.2	6.5%	3.115
541610	Management consulting services	89.8	2.2	92.0	2.4%	0.000
541512	Computer systems design services	85.5	2.6	88.1	2.9%	0.000
323110	Printing	76.2	9.2	85.3	10.7%	2.437
541200	Accounting, tax preparation, bookkeeping, and payroll services	82.8	1.0	83.8	1.2%	0.053
491000	Postal service	74.7	2.8	77.5	3.6%	0.018
3259A0	All other chemical product and preparation manufacturing	52.0	23.0	75.0	30.7%	0.000
425000	Wholesale electronic markets and agents and brokers	71.3	1.4	72.7	2.0%	0.029
811300	Commercial and industrial machinery and equipment repair and maintenance	65.2	5.5	70.7	7.8%	0.000
1111B0	Grain farming	51.6	17.5	69.1	25.3%	0.000
492000	Couriers and messengers	63.0	3.7	66.6	5.5%	0.000
230301	Nonresidential maintenance and repair	59.6	6.3	65.9	9.6%	0.000
561400	Business support services	62.3	2.7	64.9	4.1%	0.000

515100	Radio and television broadcasting	63.9	0.5	64.4	0.8%	0.680
424700	Petroleum and petroleum products	63.2	0.8	64.0	1.3%	0.416
493000	Warehousing and storage	56.4	3.3	59.7	5.5%	0.113
48A000	Scenic and sightseeing transportation and support activities for transportation	55.3	3.5	58.8	6.0%	0.196
519130	Internet publishing and broadcasting and Web search portals	53.3	2.5	55.9	4.6%	0.110
515200	Cable and other subscription programming	50.8	4.2	55.0	7.7%	1.843
517110	Wired telecommunications carriers	48.9	4.1	53.0	7.7%	1.277
811100	Automotive repair and maintenance	47.3	3.8	51.1	7.4%	0.035
S00203	Other state and local government enterprises	48.5	2.4	50.9	4.6%	0.008
325211	Plastics material and resin manufacturing	28.9	18.4	47.4	38.9%	0.010
1111A0	Oilseed farming	43.7	3.5	47.3	7.4%	0.481
423400	Professional and commercial equipment and supplies	46.4	0.8	47.2	1.7%	0.015
326190	Other plastics product manufacturing	36.7	10.0	46.6	21.4%	0.003
562000	Waste management and remediation services	40.7	4.1	44.8	9.1%	0.071
423A00	Other durable goods merchant wholesalers	42.4	1.3	43.7	3.0%	0.064
482000	Rail transportation	38.3	4.0	42.4	9.5%	0.010
5419A0	All other miscellaneous professional, scientific, and technical services	40.4	1.6	42.0	3.8%	2.664
532400	Commercial and industrial machinery and equipment rental and leasing	37.7	0.9	38.6	2.3%	0.975
517210	Wireless telecommunications carriers (except satellite)	33.0	4.6	37.6	12.2%	0.204
221200	Natural gas distribution	35.2	1.5	36.7	4.0%	0.231
322210	Paperboard container manufacturing	25.4	9.7	35.1	27.6%	0.102
722110	Full-service restaurants	33.6	1.4	35.0	4.0%	0.118
424400	Grocery and related product wholesalers	32.7	1.1	33.8	3.2%	0.048
423800	Machinery, equipment, and supplies	32.5	0.8	33.3	2.3%	0.131
518200	Data processing, hosting, and related services	31.0	2.3	33.2	6.9%	0.140
523A00	Securities and commodity contracts intermediation and brokerage	27.6	5.0	32.6	15.2%	0.066
325180	Other Basic Inorganic Chemical Manufacturing	26.1	6.3	32.4	19.4%	0.007
S00202	State and local government electric utilities	28.1	2.4	30.5	7.9%	0.036
54151A	Other computer related services, including facilities management	28.3	2.1	30.4	7.0%	0.016
325310	Fertilizer manufacturing	22.8	7.0	29.8	23.6%	0.012
511110	Newspaper publishers	28.6	0.7	29.3	2.3%	0.023
481000	Air transportation	23.0	5.9	28.8	20.3%	0.028
561900	Other support services	27.6	0.9	28.5	3.2%	0.005
561600	Investigation and security services	26.8	0.8	27.7	2.9%	0.006
811200	Electronic and precision equipment repair and maintenance	20.7	2.8	23.5	11.9%	0.099
334413	Semiconductor and related device manufacturing	22.0	1.5	23.5	0.0%	0.007
5416A0	Environmental and other technical consulting services	22.5	0.7	23.2	0.0%	0.033

Appendix H. Select Furniture Manufacturing Supply Chain (NAICS 33711, 337122)

Note: Environmental impacts are calculated using methods described in Appendix B. Calculated as a percent of total environmental impact resulting from economic activity in all U.S. industries.

		A	B	A+B	(100*B)/(A+B)	C
Code	Industry Description	Value Added ($million 2019)	Imports ($million 2019)	Total ($million 2019)	Percent Imported	Environmental Impact (1/1000th of a percent of Total U.S.)
321200	Veneer, plywood, and engineered wood product manufacturing	517.6	118.8	636.4	18.7%	0.1842
423A00	Other durable goods merchant wholesalers	565.0	17.2	582.2	3.0%	0.0006
321100	Sawmills and wood preservation	328.5	59.2	387.7	15.3%	0.0636
550000	Management of companies and enterprises	354.7	12.3	367.0	3.3%	0.0003
324110	Petroleum refineries	101.7	244.8	346.5	70.6%	0.0141
211000	Oil and gas extraction	306.2	28.9	335.1	8.6%	0.1353
113000	Forestry and logging	296.8	4.7	301.5	1.6%	0.5144
221100	Electric power generation, transmission, and distribution	265.2	20.5	285.6	7.2%	0.2274
531ORE	Other real estate	265.2	7.8	273.0	2.9%	0.0014
337215	Showcase, partition, shelving, and locker manufacturing	214.9	57.1	272.0	21.0%	0.0556
321910	Millwork	186.4	55.0	241.4	22.8%	0.0085
424A00	Other nondurable goods merchant wholesalers	229.9	5.4	235.3	2.3%	0.0002
484000	Truck transportation	223.1	11.0	234.2	4.7%	0.1142
325510	Paint and coating manufacturing	154.7	66.3	221.0	30.0%	0.0142
337121	Upholstered household furniture manufacturing	100.1	119.5	219.6	54.4%	0.0394
334413	Semiconductor and related device manufacturing	195.4	12.9	208.3	6.2%	0.0013
5419A0	All other miscellaneous professional, scientific, and technical services	149.9	5.9	155.8	3.8%	0.0000
52A000	Monetary authorities and depository credit intermediation	148.6	2.1	150.7	1.4%	0.0001
541200	Accounting, tax preparation, bookkeeping, and payroll services	144.5	1.7	146.2	1.2%	0.0000
541100	Legal services	127.9	1.5	129.5	1.2%	0.0000
444000	Building material and garden equipment and supplies dealers	126.3	1.2	127.5	0.9%	0.0001
322210	Paperboard container manufacturing	91.3	34.9	126.2	27.6%	0.0048
325211	Plastics material and resin manufacturing	73.2	46.7	119.9	38.9%	0.0112
522A00	Nondepository credit intermediation and related activities	117.1	1.9	119.0	1.6%	0.0001
541300	Architectural, engineering, and related services	112.7	5.0	117.7	4.3%	0.0000
331110	Iron and steel mills and ferroalloy manufacturing	67.4	48.9	116.3	42.1%	0.0180
561300	Employment services	113.1	1.1	114.2	1.0%	0.0000
482000	Rail transportation	103.3	10.8	114.1	9.5%	0.0221
326190	Other plastics product manufacturing	88.6	24.1	112.7	21.4%	0.0037
332500	Hardware manufacturing	83.5	28.7	112.2	25.6%	0.0005
425000	Wholesale electronic markets and agents and brokers	102.6	2.1	104.6	2.0%	0.0001
33721A	Office furniture and custom architectural woodwork and millwork manufacturing	74.1	25.3	99.4	25.5%	0.0209
561700	Services to buildings and dwellings	92.3	6.4	98.7	6.5%	0.0003

332710	Machine shops	88.7	9.4	98.1	9.6%	0.0003
332800	Coating, engraving, heat treating and allied activities	81.6	14.4	96.0	15.0%	0.0017
325110	Petrochemical manufacturing	76.0	18.7	94.6	19.7%	0.0050
326130	Laminated plastics plate, sheet (except packaging), and shape manufacturing	76.5	17.8	94.3	18.9%	0.0021
3219A0	All other wood product manufacturing	69.9	22.9	92.7	24.7%	0.0037
115000	Support activities for agriculture and forestry	84.4	5.5	89.9	6.1%	0.0098
424700	Petroleum and petroleum products	86.3	1.1	87.4	1.3%	0.0001
523A00	Securities and commodity contracts intermediation and brokerage	73.2	13.2	86.4	15.2%	0.0000
325190	Other basic organic chemical manufacturing	61.1	23.8	84.9	28.1%	0.0146
325520	Adhesive manufacturing	55.7	24.4	80.1	30.5%	0.0034
524200	Insurance agencies, brokerages, and related activities	76.0	0.5	76.6	0.7%	0.0000
541610	Management consulting services	72.8	1.8	74.6	2.4%	0.0000
481000	Air transportation	59.1	15.1	74.2	20.3%	0.0051
533000	Lessors of nonfinancial intangible assets	72.3	0.9	73.2	1.2%	0.0000
541800	Advertising, public relations, and related services	70.6	2.0	72.7	2.8%	0.0001
230301	Nonresidential maintenance and repair	61.1	6.5	67.6	9.6%	0.0025
48A000	Scenic and sightseeing transportation and support activities for transportation	63.3	4.0	67.3	6.0%	0.0079
5241XX	Insurance carriers, except direct life	55.0	12.1	67.1	18.0%	0.0000
811300	Commercial and industrial machinery and equipment repair and maintenance	60.8	5.1	65.9	7.8%	0.0001
541512	Computer systems design services	63.7	1.9	65.6	2.9%	0.0000
327200	Glass and glass product manufacturing	54.9	8.1	63.1	12.9%	0.0050
518200	Data processing, hosting, and related services	57.4	4.2	61.6	6.9%	0.0000
562000	Waste management and remediation services	53.6	5.3	59.0	9.1%	0.0123
322130	Paperboard mills	42.6	14.1	56.7	24.9%	0.0165
326110	Plastics packaging materials and unlaminated film and sheet manufacturing	41.0	15.4	56.3	27.2%	0.0008
423400	Professional and commercial equipment and supplies	54.9	0.9	55.8	1.7%	0.0001
423800	Machinery, equipment, and supplies	53.5	1.2	54.7	2.3%	0.0001
423600	Household appliances and electrical and electronic goods	52.6	1.3	53.9	2.4%	0.0001
493000	Warehousing and storage	50.7	3.0	53.6	5.5%	0.0002
721000	Accommodation	50.8	2.2	53.0	4.1%	0.0002
811100	Automotive repair and maintenance	48.7	3.9	52.6	7.4%	0.0001
517110	Wired telecommunications carriers	46.6	3.9	50.5	7.7%	0.0000
325180	Other Basic Inorganic Chemical Manufacturing	38.7	9.3	48.0	19.4%	0.0084
532400	Commercial and industrial machinery and equipment rental and leasing	46.1	1.1	47.2	2.3%	0.0000
334418	Printed circuit assembly (electronic assembly) manufacturing	34.6	12.2	46.8	26.1%	0.0001
313200	Fabric mills	37.1	9.7	46.8	20.7%	0.0006
336390	Other Motor Vehicle Parts Manufacturing	28.4	18.4	46.8	39.3%	0.0003
S00203	Other state and local government enterprises	43.7	2.1	45.9	4.6%	0.0038

Appendix I. Aggregate Net Present Value by ARC by NAICS

Values above the 80th percentile are highlighted in green. Only those ARC codes with one industry having a value above the 80th percentile is shown.

ARC Code, Two Digit Description, Three Digit Description, and 5 Digit Description	Food, Beverage, Tobacco, and Leather	Paper and Wood	Basic Organic Chemicals	Pharmaceuticals and Medicine	Furniture and Related Product
21113 Combustion Systems - FURNACES, OVENS & DIRECTLY FIRED OPERATIONS - REDUCE COMBUSTION AIR FLOW TO OPTIMUM	79.2	82.8	37.9	-	73.5
21116 Combustion Systems - FURNACES, OVENS & DIRECTLY FIRED OPERATIONS - IMPROVE COMBUSTION CONTROL CAPABILITY	73.5	85.6	67.7	-	-
21133 Combustion Systems - FURNACES, OVENS & DIRECTLY FIRED OPERATIONS - ADJUST BURNERS FOR EFFICIENT OPERATION	58.2	83.4	46.0	59.1	-
21212 Combustion Systems - BOILERS - OPERATE BOILERS ON HIGH FIRE SETTING	80.0	-	98.4	60.4	-
21221 Combustion Systems - BOILERS - REPLACE OBSOLETE BURNERS WITH MORE EFFICIENT ONES	83.1	73.4	-	17.1	64.6
21224 Combustion Systems - BOILERS - REPLACE BOILER	91.4	90.6	72.6	18.9	29.2
21232 Combustion Systems - BOILERS - KEEP BOILER TUBES CLEAN	69.9	88.1	-	22.0	-
21233 Combustion Systems - BOILERS - ANALYZE FLUE GAS FOR PROPER AIR/FUEL RATIO	95.8	93.4	90.3	88.4	37.2
21243 Combustion Systems - BOILERS - USE HEAT FROM BOILER BLOWDOWN TO PREHEAT BOILER FEED WATER	82.3	71.8	65.3	81.7	-
21311 Combustion Systems - FUEL SWITCHING - REPLACE ELECTRICALLY-OPERATED EQUIPMENT WITH FOSSIL FUEL EQUIPMENT	90.4	66.5	71.0	73.2	40.7
21321 Combustion Systems - FUEL SWITCHING - REPLACE FOSSIL FUEL EQUIPMENT WITH ELECTRICAL EQUIPMENT	81.6	79.9	-	-	-
21331 Combustion Systems - FUEL SWITCHING - BURN A LESS EXPENSIVE GRADE OF FUEL	86.5	96.9	66.1	-	-
21332 Combustion Systems - FUEL SWITCHING - CONVERT COMBUSTION EQUIPMENT TO BURN NATURAL GAS	97.1	70.2	-	-	69.9
21336 Combustion Systems - FUEL SWITCHING - INSTALL EQUIPMENT TO UTILIZE WASTE FUEL	94.3	81.8	55.6	86.6	-
21392 Combustion Systems - FUEL SWITCHING - REPLACE PURCHASED STEAM WITH OTHER ENERGY SOURCE	61.3	73.0	85.5	-	-
22113 Thermal Systems - STEAM - REPAIR OR REPLACE STEAM TRAPS	95.3	90.3	88.7	77.4	19.5
22121 Thermal Systems - STEAM - INCREASE AMOUNT OF CONDENSATE RETURNED	93.5	91.8	92.7	75.0	31.0
22122 Thermal Systems - STEAM - INSTALL / REPAIR INSULATION ON CONDENSATE LINES	51.4	21.6	20.2	81.1	-
22127 Thermal Systems - STEAM - FLASH CONDENSATE TO PRODUCE LOWER PRESSURE STEAM	53.8	80.9	-	40.2	-
22135 Thermal Systems - STEAM - REPAIR AND ELIMINATE STEAM LEAKS	96.1	95.9	91.9	65.2	14.2
22136 Thermal Systems - STEAM - INSTALL/REPAIR INSULATION ON STEAM LINES	89.4	86.8	56.5	69.5	74.3
22141 Thermal Systems - STEAM - OPERATE DISTILLATION COLUMNS EFFICIENTLY	-	-	82.3	-	-
22153 Thermal Systems - STEAM - CLOSE OFF UNNEEDED STEAM LINES	27.3	96.2	-	-	-
22162 Thermal Systems - STEAM - REDUCE EXCESS STEAM BLEEDING	62.1	84.3	-	9.8	-

22211 Thermal Systems - HEATING - USE OPTIMUM TEMPERATURE	27.5	39.2	94.4	-	61.9
22414 Thermal Systems - HEAT RECOVERY - USE WASTE HEAT FROM HOT FLUE GASES TO PREHEAT	98.2	97.2	96.8	93.9	78.8
22423 Thermal Systems - HEAT RECOVERY - INSTALL WASTE HEAT BOILER TO PRODUCE STEAM	-	-	91.1	96.3	-
22425 Thermal Systems - HEAT RECOVERY - USE FLUE GASES TO HEAT PROCESS OR SERVICE WATER	91.9	43.9	-	79.9	-
22427 Thermal Systems - HEAT RECOVERY - USE WASTE HEAT FROM HOT FLUE GASES TO PREHEAT INCOMING FLUIDS	63.9	89.7	-	-	82.3
22437 Thermal Systems - HEAT RECOVERY - RECOVER WASTE HEAT FROM EQUIPMENT	99.0	97.8	99.2	92.1	89.4
22441 Thermal Systems - HEAT RECOVERY - PREHEAT BOILER MAKEUP WATER WITH WASTE PROCESS HEAT	92.5	96.6	11.3	68.9	-
22442 Thermal Systems - HEAT RECOVERY - PREHEAT COMBUSTION AIR WITH WASTE HEAT	89.6	82.1	32.3	52.4	-
22444 Thermal Systems - HEAT RECOVERY - USE HOT PROCESS FLUIDS TO PREHEAT INCOMING PROCESS FLUIDS	93.2	87.5	61.3	-	-
22445 Thermal Systems - HEAT RECOVERY - RECOVER HEAT FROM EXHAUSTED STEAM	83.6	95.3	78.2	-	-
22446 Thermal Systems - HEAT RECOVERY - RECOVER HEAT FROM HOT WASTE WATER	71.7	92.2	-	-	-
22447 Thermal Systems - HEAT RECOVERY - HEAT WATER WITH EXHAUST HEAT	95.1	2.2	-	-	-
22492 Thermal Systems - HEAT RECOVERY - USE “HEAT WHEEL” OR OTHER HEAT EXCHANGER TO CROSS-EXCHANGE BUILDING EXHAUST AIR WITH MAKE-UP AIR	55.6	48.0	38.7	87.2	23.0
22511 Thermal Systems - HEAT CONTAINMENT - INSULATE BARE EQUIPMENT	94.8	93.1	83.1	54.3	66.4
22615 Thermal Systems - COOLING - CLEAN CONDENSER TUBES	8.8	9.4	87.9	-	-
22621 Thermal Systems - COOLING - MODIFY REFRIGERATION SYSTEM TO OPERATE AT A LOWER PRESSURE	96.6	11.6	0.8	75.6	-
22622 Thermal Systems - COOLING - REPLACE EXISTING CHILLER WITH HIGH EFFICIENCY MODEL	90.9	55.2	71.8	95.1	-
22628 Thermal Systems - COOLING - UTILIZE A LESS EXPENSIVE COOLING METHOD	90.1	68.7	13.7	74.4	-
22696 Thermal Systems - COOLING - USE EXCESS COLD PROCESS FLUID FOR INDUSTRIAL COOLING NEEDS	85.5	-	-	-	-
23131 Electrical Power - DEMAND MANAGEMENT - RESCHEDULE PLANT OPERATIONS OR REDUCE LOAD TO AVOID PEAKS	82.9	80.3	97.6	42.1	81.4
23192 Electrical Power - DEMAND MANAGEMENT - USE FOSSIL FUEL POWERED GENERATOR DURING PEAK DEMAND PERIODS	81.0	67.4	-	44.5	-
23212 Electrical Power - POWER FACTOR - OPTIMIZE PLANT POWER FACTOR	94.5	91.2	79.8	70.1	85.8
23321 Electrical Power - GENERATION OF POWER - USE STEAM PRESSURE REDUCTION TO GENERATE POWER	84.7	78.4	89.5	-	0.0
23411 Electrical Power - COGENERATION - REPLACE ELECTRIC MOTORS WITH BACK PRESSURE STEAM TURBINES AND USE EXHAUST STEAM FOR PROCESS HEAT	53.2	94.4	-	-	-
23413 Electrical Power - COGENERATION - BURN FOSSIL FUEL TO PRODUCE STEAM TO DRIVE A STEAM TURBINE-GENERATOR AND USE STEAM EXHAUST FOR HEAT	81.3	59.9	-	-	69.0
23414 Electrical Power - COGENERATION - BURN WASTE TO PRODUCE STEAM TO DRIVE A STEAM TURBINE GENERATOR SET AND USE STEAM EXHAUST FOR HEAT	43.4	99.1	-	-	99.1
23415 Electrical Power - COGENERATION - USE A FOSSIL FUEL ENGINE TO COGENERATE ELECTRICITY OR MOTIVE POWER; AND UTILIZE HEAT	97.4	82.4	95.2	67.1	79.6
23416 Electrical Power - COGENERATION - USE COMBINED CYCLE GAS TURBINE GENERATOR SETS WITH WASTE HEAT BOILERS CONNECTED TO TURBINE EXHAUST	88.8	68.0	69.4	82.9	-
23417 Electrical Power - COGENERATION - USE WASTE HEAT WITH A CLOSED-CYCLE GAS TURBINE-GENERATOR SET TO COGENERATE ELECTRICITY AND HEAT	83.4	75.2	96.0	-	-
24111 Motor Systems - MOTORS - UTILIZE ENERGY-EFFICIENT BELTS AND OTHER IMPROVED MECHANISMS	88.3	93.7	33.1	68.3	80.5

24133 Motor Systems - MOTORS - USE MOST EFFICIENT TYPE OF ELECTRIC MOTORS	92.2	89.0	86.3	66.5	70.8
24146 Motor Systems - MOTORS - USE ADJUSTABLE FREQUENCY DRIVE OR MULTIPLE SPEED MOTORS ON EXISTING SYSTEM	99.5	98.1	93.5	98.8	96.5
24221 Motor Systems - AIR COMPRESSORS - INSTALL COMPRESSOR AIR INTAKES IN COOLEST LOCATIONS	86.2	76.2	54.0	63.4	65.5
24224 Motor Systems - AIR COMPRESSORS - UPGRADE CONTROLS ON COMPRESSORS	92.7	92.5	21.0	58.5	92.0
24226 Motor Systems - AIR COMPRESSORS - USE / PURCHASE OPTIMUM SIZED COMPRESSOR	87.8	84.6	33.9	70.7	59.3
24236 Motor Systems - AIR COMPRESSORS - ELIMINATE LEAKS IN INERT GAS AND COMPRESSED AIR LINES/ VALVES	98.4	97.5	80.6	92.7	95.6
24239 Motor Systems - AIR COMPRESSORS - ELIMINATE OR REDUCE COMPRESSED AIR USAGE	96.9	95.6	62.9	84.8	94.7
24321 Motor Systems - OTHER EQUIPMENT - UPGRADE OBSOLETE EQUIPMENT	67.0	88.7	-	78.7	9.7
24322 Motor Systems - OTHER EQUIPMENT - USE OR REPLACE WITH ENERGY EFFICIENT SUBSTITUTES	97.9	81.5	52.4	45.1	54.9
24323 Motor Systems - OTHER EQUIPMENT - USE OPTIMUM SIZE AND CAPACITY EQUIPMENT	79.0	88.4	-	32.9	-
25194 Industrial Design - SYSTEMS - REDESIGN PROCESS	80.5	76.5	68.5	80.5	-
25195 Industrial Design - SYSTEMS - CHANGE PRODUCT DESIGN TO REDUCE ENERGY REQUIREMENTS	63.1	64.9	-	82.3	-
26218 Operations - EQUIPMENT CONTROL - TURN OFF EQUIPMENT WHEN NOT IN USE	94.0	86.2	28.2	93.3	85.0
26221 Operations - EQUIPMENT CONTROL - USE MOST EFFICIENT EQUIPMENT AT ITS MAXIMUM CAPACITY AND LESS EFFICIENT EQUIPMENT ONLY WHEN NECESSA	81.8	63.3	50.0	84.1	-
26231 Operations - EQUIPMENT CONTROL - UTILIZE CONTROLS TO OPERATE EQUIPMENT ONLY WHEN NEEDED	93.8	79.6	79.0	57.3	28.3
27135 Building and Grounds - LIGHTING - INSTALL OCCUPANCY SENSORS	90.6	84.0	54.8	83.5	84.1
27142 Building and Grounds - LIGHTING - UTILIZE HIGHER EFFICIENCY LAMPS AND/OR BALLASTS	99.7	98.4	84.7	97.6	98.2
27221 Building and Grounds - SPACE CONDITIONING - LOWER TEMPERATURE DURING THE WINTER SEASON AND VICE-VERSA	77.7	52.4	36.3	94.5	68.1
27224 Building and Grounds - SPACE CONDITIONING - REDUCE SPACE CONDITIONING DURING NON-WORKING HOURS	80.3	57.7	18.5	43.9	83.2
27226 Building and Grounds - SPACE CONDITIONING - USE COMPUTER PROGRAMS TO OPTIMIZE HVAC PERFORMANCE	52.7	23.8	-	90.2	-
27231 Building and Grounds - SPACE CONDITIONING - USE RADIANT HEATER FOR SPOT HEATING	72.2	77.1	53.2	-	86.7
27232 Building and Grounds - SPACE CONDITIONING - REPLACE EXISTING HVAC UNIT WITH HIGH EFFICIENCY MODEL	76.6	61.4	19.4	90.9	0.9
27241 Building and Grounds - SPACE CONDITIONING - INSTALL OUTSIDE AIR DAMPER / ECONOMIZER ON HVAC UNIT	70.4	57.1	49.2	55.5	87.6
27252 Building and Grounds - SPACE CONDITIONING - UTILIZE AN EVAPORATIVE AIR PRE-COOLER OR OTHER HEAT EXCHANGER IN AC SYSTEM	48.1	3.4	-	86.0	-
27313 Building and Grounds - VENTILATION - RECYCLE AIR FOR HEATING, VENTILATION AND AIR CONDITIONING	26.5	70.8	-	97.0	34.5
27314 Building and Grounds - VENTILATION - REDUCE VENTILATION AIR	75.1	67.1	63.7	91.5	88.5
27425 Building and Grounds - BUILDING ENVELOPE - CLEAN OR COLOR ROOF TO REDUCE SOLAR LOAD	67.5	2.8	-	95.7	-
27447 Building and Grounds - BUILDING ENVELOPE - INSTALL VINYL STRIP / HIGH SPEED / AIR CURTAIN DOORS	88.1	63.0	-	64.6	77.9
28112 Ancillary Costs - ADMINISTRATIVE - COMBINE UTILITY METERS	80.8	60.8	-	3.7	-

28113 Ancillary Costs - ADMINISTRATIVE - PURCHASE GAS DIRECTLY FROM A CONTRACT GAS SUPPLIER	86.8	79.3	-	48.2	-
28114 Ancillary Costs - ADMINISTRATIVE - CHANGE RATE SCHEDULES OR OTHER CHANGES IN UTILITY SERVICE	93.0	78.1	34.7	89.6	92.9
28121 Ancillary Costs - ADMINISTRATIVE - APPLY FOR TAX-FREE STATUS FOR ENERGY PURCHASES	88.6	62.7	8.1	57.9	91.2
29141 Alternative Energy Usage - GENERAL - INSTALL ANAEROBIC DIGESTER	91.2	-	-	-	-
31163 Operations - PROCEDURES - USE PLASTIC PALLETS INSTEAD OF WOOD	-	90.9	-	-	-
31181 Operations - PROCEDURES - ELIMINATE A BY-PRODUCT	72.7	80.6	-	-	-
31182 Operations - PROCEDURES - MAKE A NEW BY-PRODUCT	85.2	69.3	-	-	-
31191 Operations - PROCEDURES - CHANGE PROCEDURES / EQUIPMENT / OPERATING CONDITIONS	91.7	94.0	-	-	8.8
31192 Operations - PROCEDURES - REDUCE SCRAP PRODUCTION	84.2	63.6	-	-	-
33128 Post Generation Treatment / Minimization - GENERAL - UTILIZE OTHER METHODS TO REMOVE CONTAMINANTS	87.5	-	83.9	99.4	-
34111 Water Use - GENERAL - USE CLOSED CYCLE PROCESS TO MINIMIZE WASTE WATER PRODUCTION	85.7	27.3	41.9	73.8	-
34113 Water Use - GENERAL - TREAT AND REUSE RINSE WATERS	82.6	37.0	-	-	-
34114 Water Use - GENERAL - REPLACE CITY WATER WITH RECYCLED WATER VIA COOLING TOWER	86.0	36.7	59.7	45.7	-
34115 Water Use - GENERAL - RECOVER AND REUSE COOLING WATER	74.3	11.9	81.5	35.4	-
34131 Water Use - GENERAL - MINIMIZE CONTAMINATION OF WATER BEFORE TREATMENT	83.9	35.7	-	-	-
34151 Water Use - GENERAL - MINIMIZE WATER USAGE	84.9	34.8	15.3	62.8	15.0
35317 Recycling - OTHER MATERIALS - SELL / OFFER BY-PRODUCT AS ANIMAL FEED	82.1	60.5	-	-	-
36112 Waste Disposal - GENERAL - USE FILTER AND DRYING OVEN TO REDUCE SLUDGE VOLUME	78.4	83.1	-	-	-
36123 Waste Disposal - GENERAL - BURN WOOD BY-PRODUCTS FOR HEAT	-	64.6	-	-	97.3
36124 Waste Disposal - GENERAL - BURN WASTE OIL FOR HEAT	15.8	30.4	-	89.0	-
36193 Waste Disposal - GENERAL - INSTALL EQUIPMENT (E.G. COMPACTOR) TO REDUCE DISPOSAL COSTS	66.0	48.6	-	98.2	76.1
41110 Manufacturing Enhancements - BOTTLENECK REDUCTION - ADD EQUIPMENT/ OPERATORS TO REDUCE PRODUCTION BOTTLENECK	97.7	99.7	-	87.8	90.3
41130 Manufacturing Enhancements - BOTTLENECK REDUCTION - INSTALL REFRIGERATION SYSTEM TO COOL PRODUCT	73.8	-	87.1	-	-
41140 Manufacturing Enhancements - BOTTLENECK REDUCTION - ADD/MODIFY EQUIPMENT TO IMPROVE DRYING PROCESS	95.6	87.1	-	-	-
41220 Manufacturing Enhancements - DEFECT REDUCTION - DEVELOP STANDARD PROCEDURES TO IMPROVE INTERNAL YIELDS	87.3	87.8	-	-	-
41250 Manufacturing Enhancements - DEFECT REDUCTION - MODIFY PROCESS TO REDUCE MATERIAL COSTS	56.1	85.3	-	-	-
41310 Manufacturing Enhancements - MATERIAL REDUCTION - MODIFY PROCESS TO REDUCE MATERIAL USE/COST	70.1	94.7	-	-	-
41320 Manufacturing Enhancements - MATERIAL REDUCTION - PURCHASE NEW EQUIPMENT TO REDUCE MATERIAL USE / COST	89.1	89.3	-	-	-
44210 Labor Optimization - PRACTICES / PROCEDURES - MODIFY CURRENT INCENTIVE PROGRAM	-	92.8	-	-	-
44230 Labor Optimization - PRACTICES / PROCEDURES - MOVE PRODUCT USING MECHANICAL MEANS	68.3	85.9	-	-	-

44310 Labor Optimization - TRAINING - TRAIN OPERATORS FOR MAXIMUM OPERATING EFFICIENCY	87.0	77.4	-	-	43.4
44410 Labor Optimization - AUTOMATION - INSTALL AUTOMATIC PACKING EQUIPMENT	99.2	91.5	-	53.7	-
44450 Labor Optimization - AUTOMATION - INSTALL EQUIPMENT TO MOVE PRODUCT	76.9	90.0	-	-	-
44460 Labor Optimization - AUTOMATION - AUTOMATE FINISHING PROCESS	19.7	95.0	-	-	-
44510 Labor Optimization - SCHEDULING - ADD ADDITIONAL PRODUCTION SHIFT	84.4	72.7	-	-	-
44530 Labor Optimization - SCHEDULING - RESCHEDULE BREAKS TO ALLOW FOR CONTINUOUS PRODUCTION	-	98.7	-	-	-
44540 Labor Optimization - SCHEDULING - MODIFY STARTUP/SHUTDOWN TIMES	22.3	55.8	-	-	93.8
46110 Reduction of Downtime - MAINTENANCE - BEGIN A PRACTICE OF PREDICTIVE / PREVENTATIVE MAINTENANCE	89.9	62.1	-	14.0	61.1
46210 Reduction of Downtime - QUICK CHANGE - USE FIXTURES TO REDUCE MACHINE CHANGEOUT TIMES	-	85.0	-	-	-
46230 Reduction of Downtime - QUICK CHANGE - EMPLOY MODULAR JIGS TO REDUCE PROCESS SET-UP TIME	-	81.2	-	-	-
46250 Reduction of Downtime - QUICK CHANGE - DEVELOP STANDARD OPERATING PROCEDURES	29.4	86.5	-	-	-
46310 Reduction of Downtime - POWER CONDITIONING - INSTALL AN UNINTERRUPTIBLE POWER SUPPLY	98.7	50.5	-	-	-
46510 Reduction of Downtime - OTHER EQUIPMENT - INSTALL BACKUP EQUIPMENT	71.9	83.7	-	-	-
46520 Reduction of Downtime - OTHER EQUIPMENT - REPLACE EXISTING EQUIPMENT WITH MORE SUITABLE SUBSTITUTES	96.4	99.4	-	85.4	-