The US bioeconomy at the intersection of technology, policy, and education

Danielle U Pascoli, School of Environmental and Forest Sciences, University of Washington, Seattle, WA, USA
Alvina Aui, Department of Mechanical Engineering, Iowa State University, Ames, IA, USA
Jenny Frank, Obste Therasme, Department of Sustainable Resources Management, SUNY College of Environmental Science and Forestry, Syracuse, NY, USA
Kerry Dixon, Beta by Design, Columbus, OH, USA
Rick Gustafson, School of Environmental and Forest Sciences, University of Washington, Seattle, WA, USA
Brendan Kelly, Fiber and Biopolymer Research Institute, Texas Tech University, Lubbock, TX, USA; Texas A&M AgriLife Research, Lubbock, TX, USA
Timothy A Volk, Department of Sustainable Resources Management, SUNY College of Environmental Science and Forestry, Syracuse, NY, USA
Mark M Wright, Department of Mechanical Engineering, Iowa State University, Ames, IA, USA

Received July 09 2021; Revised September 04 2021; Accepted September 21 2021; View online October 13, 2021 at Wiley Online Library (wileyonlinelibrary.com); DOI: 10.1002/bbb.2302; Biofuels, Bioprod. Bioref. 16:9–26 (2022)

Abstract: The bioeconomy is a complex, multivariate, and interdisciplinary system that requires a comprehensive assessment of its independent parts if it is to be understood fully. Hence, this article presents a holistic perspective of industry, public policy, and education aspects of the US bioeconomy. It is premised on the idea that a successful bioeconomy industry relies on the balanced development of all stages of the supply chain. For this balance to be struck, a strong interdisciplinary workforce must find novel solutions to multifaceted problems across the entirety of the supply chain. These solutions require innovative technologies that can improve the climate benefit of bioproducts, decrease their production costs, and make them more economically competitive. Increasing consumer education and awareness about the bioeconomy goes hand in hand with the development of a robust market for bioproducts. To guide these interdependent efforts, public policies must encourage demand, support competitive markets, promote the entry of renewable options, and stimulate growth by reducing financial barriers. We contend that a combination of policies is likely to be more effective than any singular policy on its own. Supporting the bioeconomy also entails attending to an existing lack of public awareness as well as workforce-ready professionals. To address these gaps, the USA must increase the intensity and intentionality of its efforts to educate students about the bioeconomy, particularly at the K-12 level. Furthermore, these efforts should encompass both formal and informal learning contexts in order to meet the workforce challenges facing the bioeconomy now and in the future. © 2021 The Authors. Biofuels, Bioproducts and Biorefining published by Society of Industrial Chemistry and John Wiley & Sons Ltd.
Key words: bioeconomy; industry; technological development; public policy; education; workforce development

Introduction

Climate change, food, energy security, and ecosystem degradation in relation to the growing human population and limited natural resources represent major global challenges of the 21st century. The world’s population is expected to grow from 7.8 billion people in 2019 to 10.1 billion in 2060. This population growth will inevitably result in increased demand for finite and limited natural resources, which are needed to produce food, raw materials, products, and energy. Compounding the impending crisis is our current and historic reliance on fossil-based resources (e.g., coal, natural gas, and oil), which is the primary contributor to the increased concentration of greenhouse gases (GHG) in the atmosphere, resulting in global warming. In fact, between 1880 and 2012 the average surface temperature of the earth rose by 0.85 °C due to anthropogenic activities and it will continue to increase in the absence of adapted actions to stabilize the carbon dioxide concentration in the atmosphere. One of the many consequences of higher global average temperatures is the dramatically increased frequency and recovery costs of climate disasters, resulting in billions of dollars of monetary losses and incalculable losses in terms of human life and social infrastructure.

In response to these problems, the world has gradually been transitioning to a bioeconomy in which renewable biological resources replace fossil resources used in the generation of energy and other consumer products. Biomass that is produced and used in a variety of different pathways and applications in the bioeconomy is projected to play a critical role in addressing the challenges associated with climate change. For example, in the Intergovernmental Panel on Climate Change (IPCC) pathways that limit global warming to 1.5 °C with limited or no overshoot, Carbon Dioxide Removal (CDR) practices play a key role in removing somewhere between 100 to 1000 Gt CO₂ during the 21st century, with bioenergy carbon capture and sequestration (BECCS) systems contributing between 43–98% of the CDR. In addition to CDR, biomass is projected to play an essential role in decarbonizing a range of sectors in the global economy by replacing fossil fuels in energy systems and by storing CO₂ removed from the atmosphere in long-life products such as mass timber, bioplastics, and biochar. Under certain conditions, using biomass for bioenergy can lead to net negative GHG, but recent analysis suggests that the carbon storage value associated with biomass may exceed its energy value causing a shift in the way that biomass is used to address the climate change challenge.

Given the emergent nature of the sector, the concept of bioeconomy is constantly evolving and varies significantly between nations and their respective economies, natural resource availability, and technologies. In the USA, the National Bioeconomy Blueprint of 2012 defined the bioeconomy as ‘one based on the use of research and innovation in the biological sciences to create economic activity and public benefit’. In 2014, the bioeconomy was further described as ‘the global industrial transition of sustainably utilizing renewable aquatic and terrestrial biomass resources in energy, intermediate, and final products for economic, environmental, social, and national security benefits’. This latter definition, which was adopted by the US Biomass Research and Development Board in its reports, auspiciously conveyed the notion of sustainability pillars, arguing that a successful bioeconomy is capable of providing the country with environmental, economic, and social benefits (Fig. 1).

Efforts to promote the US bioeconomy began as early as 2000 when the Biomass Research and Development Act of 2000 acknowledged the benefits of converting biomass feedstocks into biobased products and fuels as well as the need for cost-competitive technologies. Soon thereafter, the Renewable Fuel Standard (RFS) program became the first national policy to require the use of renewable alternatives to petroleum-based fuels. In 2005, the Department of Energy (DOE) published its Billion-Ton Study (BTS), which estimated the US biomass potential based on production capacity, biomass availability, and available technology. In 2011, 2016, and 2017, the DOE updated the Billion-Ton Study, including information such as biomass feedstock prices, non-conventional feedstocks, and environmental effects of potential biomass production scenarios in the USA. The National Bioeconomy Blueprint, produced by the Obama administration in 2012, set forth five strategic objectives related to growing the US bioeconomy. These objectives were: (i) supporting research and development investments, (ii) facilitating the transition from lab-scale production to market scale, (iii) developing regulations to promote innovation and market expansion, (iv) enhancing education and training to develop the national bioeconomy workforce, and (v) fostering public-private collaborations. Together, all of the initiatives described above constitute
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the most aggressive steps taken by the US government to promote the bioeconomy’s development. Yet, many challenges remain in achieving the full potential of this vast and rapidly growing sector.

As is the case with all systems that will be scaled up to address global and regional challenges, a set of agreed sustainability metrics needs to be developed to minimize the impact and maximize the benefit associated with the expanded role of the bioeconomy. Such sustainability metrics should encompass environmental and socioeconomic indicators, such as soil and water quality, biodiversity, air quality, energy security, profitability, resource conservation, social acceptability, food security, and more. When these sustainability metrics are used along with effective stakeholder engagement, they can expose potential trade-offs in different parts of the system and help to build the bioeconomy in a careful and wise manner.5,15

In this article, we start from the premise that the bioeconomy is a complex, multivariate, and interdisciplinary system, the independent parts of which must be addressed in relation to each other for the whole to progress and thrive. We focus primarily on how the needs of the bioeconomy’s industrial sector intersect with public policy and how young people are being prepared to become the interdisciplinary, skilled workforce the bioeconomy requires. The need to prepare the future workforce is of particular interest to us as authors, as we share the experience of participating in the Consortium for Advanced Bioeconomy Leadership Education (CABLE). This is an initiative that links 21 universities and dozens of industry partners nationwide to create and sustain a pipeline of future bioeconomy workforce leaders. The initiative is funded by the National Institute of Food and Agriculture (NIFA) at the United States Department of Agriculture (USDA).

This article thus presents our holistic perspective on the current state and future potential of the US bioeconomy through the lens of technological development, public policy, and education. We begin by presenting a brief synthesis of major drivers of the bioeconomy industry, potential supply-chain needs that require a unique workforce, particular challenges in advancing the different supply-chain stages, and the importance of consumer awareness to promote a robust market for bioproducts. Then, we describe existing bioeconomy-related policies in the USA, discussing both their strengths and challenges. Finally, we provide a broad overview of how education is organized in the USA, then argue for the integration of an explicit bioeconomy education at the K-12, undergraduate, and graduate levels so that a skilled interdisciplinary bioeconomy workforce will ultimately guide us forward into a sustainable world.

Industry

The bioeconomy industry is responsible for the production and commercialization of a diversity of products derived from renewable biomass. These products (commonly referred to as biobased products or simply as bioproducts) can be encountered in various industrial sectors with a wide range of markets and applications. Examples include biopolymers, bioplastics, biofuels, biosurfactants, pulp and paper, wood products, food additives, pharmaceuticals, and many more. The USDA BioPreferred Program defines a bioproduct as a ‘commercial or industrial product (other than food or feed) that is (A) composed, in whole or in

Figure 1. Examples of environmental, economic, and social outcomes of a successful bioeconomy.9

| Environmental, social, and economic benefits |
|---------------------------------------------|
| Reduced greenhouse gas emissions (associated with replacement of fossil-fuels by renewable alternatives) |
| Optimized land use, improved water and soil quality, and increased food security (associated with sustainable and efficient biomass production system) |
| Increased job growth and workforce development in various sectors |
| Rural development (associated with economic development resulting from sustainable biomass production) |
| Increased national revenue from commercialization of biobased products |
| National security (associated with lower dependence on foreign oil and its volatile prices) |
significant part, of biological products, including renewable domestic agricultural materials, renewable chemicals, and forestry materials; or (B) an intermediate ingredient or feedstock.\textsuperscript{16} Furthermore, the modern bioeconomy’s primary focus has been the production of advanced bioproducts, excluding food, feed, and other conventional biomass-derived products.\textsuperscript{16,17} Broadly speaking, the main objective of the modern bioeconomy is to provide added value to the country’s economy through these bioproducts while ensuring sustainability remains central to the endeavor.

Advanced bioproducts generally provide a sustainable alternative to existing petroleum-based products. Biochemicals and biomaterials have gained attention steadily in recent years due to an increased demand for biobased alternatives within various industries, including food and beverage, packaging, automotive, pharmaceutical, personal care, paint and coatings, and more.\textsuperscript{18} The global biochemicals market is expected to grow with a compound annual growth rate (CAGR) of over 10% between 2019 and 2025, with bioplastics, biolubricants, and other biosolvents representing the materials that are most in demand.\textsuperscript{18} The popularity of bioproducts such as these arises mostly from their potential to contribute to national security by reducing the reliance on other countries and also their sustainability related characteristics, attracting not only consumers but also suppliers, manufacturers, and retailers that share these same values.

Given these qualities, companies from many different sectors have pledged to leverage bioproducts in meeting their sustainability targets. For instance, the Ford Motor Company has begun to use biobased materials in its automotive products, such as soy-based foam for seat cushions, dashboards padded with scrap cotton, and storage bins made from wheat straw. In addition, the company has undertaken massive marketing campaigns to increase its market share of cars fueled by biofuels.\textsuperscript{19} Although the public’s interest in electrical vehicles has been increasing lately, the potential of liquid biofuels for small vehicles should not be undermined. Heavy-load transit, sustainable aviation fuel, and marine fuel will continue to create a demand for liquid biofuels because it is difficult to electrify these systems. Unilever, for example, is engaged in several sustainability initiatives, including using second-generation biofuels made from nonfood ingredients for ground transport.\textsuperscript{20} Given the realities of climate change and resource depletion, examples like these will undoubtedly increase in the future, expanding the bioeconomy market exponentially.\textsuperscript{21}

The bioeconomy supply chain

Numerous stakeholders across the bioeconomy supply chain contribute to the bioproducts industry. The supply chain can be simplified into three main stages as illustrated in Fig. 2. The first stage involves \textit{biomass production and handling}, which is responsible for growing the biomass that will eventually be used as a raw material in conversion facilities. The second stage is the \textit{conversion process and product manufacturing}, whereby biomass is fractionated into its components then subsequently converted into valuable final products. Finally, the third stage is \textit{product marketing and end use}, which comprises the marketing of bioproducts, their utilization by consumers, and the recovery of waste within the supply chain. These three stages are highly interdependent and the success or failure of one of them can affect the performance of the entire chain. For instance, a deficiency in biomass production will compromise product manufacturing. Similarly, a lack of demand (i.e., consumers) will jeopardize the profitability of both the conversion facilities and the biomass producers. The success of the entire bioeconomy

![Figure 2. Simplified bioeconomy supply chain.](image-url)
industry sector therefore requires a balanced development of all stages of the supply chain.

To achieve a balanced development, a strong interdisciplinary workforce must be engaged across the entirety of the supply chain. With the bioeconomy poised to generate 1.1 million jobs by 2030, professionals with a wide range of knowledge and skills must be prepared. This includes farmers, natural resource managers, scientists, social scientists, engineers, managers, construction workers, economists, analysts, educators, market and business specialists, and more. The diversity, complexity, and interdisciplinarity of this array inherently requires that individuals develop not only expertise in their particular fields but also a broad knowledge of other areas in order to collaborate effectively and communicate with maximum efficiency.

In addition to workforce development, factors such as policy uncertainty, technical constraints, and competition with petroleum-derived resources present key challenges for the growth of the bioeconomy. In particular, governmental investment in new biobased technologies and infrastructure is crucial. Equally important, R&D must be prioritized to establish cost-effective and environmentally friendly processes that can make bioproducts more economically competitive with oil-based alternatives.

### Biomass production and handling stage

There are many types of sustainably produced biomass in the USA. Existing biomass sources primarily consisted of agricultural resources (corn grains, vegetable oils, fats, greases) and forestry resources (wood pellets, wood logs, wood chips). A third type consisted of waste resources, including agricultural wastes (corn stover, wheat straw, cotton field residues, soybean hulls), forestry wastes (mill wastes, pulping liquor), and municipal solid waste. Along with these three types, the BTS identified additional resources that could enable the USA to produce sustainably 1 billion tons of biomass annually. Among them, energy crops (including herbaceous and woody crops such as switchgrass, miscanthus, sorghum, energy cane, willow, poplar, eucalyptus, and pine) have the potential to become the USA’s leading biomass source by 2030. Table 1 provides a summary of US biomass production capacity in 2017 versus 2030 and includes both existing and potential resources. Furthermore, algae are another prospective feedstock that could provide fuel production yields superior to that of terrestrial feedstocks.

| Table 1. Summary of sustainably produced biomass in the USA in 2017 and 2030 (at $60 per dry ton or less). Adapted from Langholtz et al. (2016). |
|---------------------------------------------------------------|
| **Conventional bioproducts**                                   | **Production** |
| **Existing resources**                                        | (million dry tons) |
| Forestry resources                                            | 154            | 154 |
| Agricultural resources                                        | 144            | 144 |
| Waste resources                                               | 68             | 68  |
| **Potential resources**                                       |                |     |
| Forestry resources (all timberland)                          | 95             | 87  |
| Agricultural residues                                        | 105            | 174 |
| Energy crops*                                                | 0              | 380 |
| Waste resources                                               | 137            | 140 |
| **Total (conventional + potential)**                          | 702            | 1147|

2030 projections correspond to BTS high-yield scenario assumption of a 3% annual increase in yield. *Energy crops were assumed to be planted starting in 2019.

The biomass production and handling stage holds a key to making the bioeconomy cost competitive. In fact, techno-economic studies have shown that biomass feedstock is the biggest contributor (up to 55%) to the total manufacturing cost of lignocellulosic ethanol, for example. This high biomass cost is associated with several factors. First, biomass is bulky and grows dispersed throughout the landscape, which leads to high transportation costs. Second, seasonal crops that are harvested at specific times of the year create a dependency problem whereby any periodic scarcity can result in a significant economic impact across the supply chain. Third, using low-quality feedstocks that have an inferior chemical composition and higher recalcitrance results in lower conversion yields. As a result, manufacturing costs per unit of final product can dramatically increase. Finally, productivity and variation in quality of the biomass directly impacts the final cost to end users. Biomass is inherently susceptible to quality loss (e.g., carbohydrate content, moisture, and morphology) during storage. Hence, advanced storage and handling practices can be used to extend the shelf life and minimize compositional variability of biomass, which also increases the production costs.

Given these challenges, various strategies to increase productivity and reduce production costs are currently being explored. One of the most noteworthy of these is the use of low-cost feedstocks (such as agricultural and forestry wastes) as raw material in conversion processes. To overcome seasonal dependencies, biomass can be stored under controlled conditions to maintain the quality of the biomass and reduce the amount of dry matter lost during the storage period. Some R&D also focuses on new conversion processes that can utilize different types of feedstocks concurrently, thus lowering the economic vulnerability of conversion facilities and resulting in a more consistent
production throughout the year.\textsuperscript{35} Crop development techniques (including conventional and biotechnological) are also being used to develop higher quality crops with suitable chemical composition. These techniques aim to increase productivity at both farms and conversion facilities. For example, advanced breeding lines of crops can be developed via conventional mating techniques to improve their fermentability to ethanol.\textsuperscript{36} Another promising strategy involves the use of an intensively managed short-rotation coppice system to produce more woody biomass in a shorter period of time. Short-rotation woody crops are fast-growing woody biomass species (such as poplar and willow) that can yield large amounts of biomass with harvesting cycles as short as 3 years.\textsuperscript{37} In addition, the BTS report argued that, because the trees are considerably smaller as a result of the shorter harvesting cycles, they can be harvested using more efficient machinery to reduce harvesting costs.\textsuperscript{13}

As the bioeconomy expands, biomass production will need to scale accordingly, resulting in increased land use. A sustainable framework for biomass production is, therefore, essential to ensure that competition for land and other natural resources is limited. The framework must also prioritize diminishing the negative environmental impacts associated with land use. One possible approach focuses on growing non-food crops in \textit{marginal lands}, which include nonconventional lands such as abandoned cropland, grasslands, rangeland, and pastureland.\textsuperscript{38,39} Marginal lands often consist of low-nutrient and erosion-prone soils that cannot support the production of food crops but can be sufficient for growing energy crops for the bioeconomy.\textsuperscript{39} Moreover, the intentional growth of specific crops in marginal lands has the added benefit of enhancing biodiversity as well as improving soil and water quality by filtering contaminants. This process increases soil porosity and water infiltration and increases the amount of carbon in the soil.\textsuperscript{40} In addition, because marginal lands are available across the country’s landscape, transportation costs can be reduced by growing biomass near the conversion facilities. Thus, the approach of using marginal lands to scale biomass production holds great promise in terms of its positive environmental, social, and economic impacts.

\textbf{Conversion process and product manufacturing stage}

The process of biomass conversion into intermediate or final bioproducts is commonly referred to as the \textit{biorefinery concept}, which is analogous to a petroleum refinery where a single raw material (either biomass or petroleum) is converted into multiple fuels, chemicals, and other products.\textsuperscript{41} Biomass conversion is a very complex system because it encompasses different types of feedstocks (each with its unique chemical composition and inherent challenges) and different types of conversion processes. In general, four main types of conversion processes can be used (mechanical/physical, chemical, thermochemical, and biochemical), and within each type, there are a number of methods and techniques available with distinct outcomes. Thus, choosing the best process for a biorefinery depends on both the type of feedstock and the products being generated,\textsuperscript{41} resulting in a multitude of pathways (Fig. 3).\textsuperscript{42} In general, biomass conversion to intermediate or final products is often costly because it requires multi-step processes, each requiring different conversion mechanisms including advanced technologies and expensive catalysts.

The variability of feedstocks and associated processes has the potential to be both beneficial and disadvantageous to the development of the industry. One primary advantage lies in the opportunity for an exponential increase in technological innovations necessitated by the multiplicities of conversion pathways. At the same time, the number of variables associated with choosing from a wide range of feedstocks and processes can become quickly complicated. For example, using low-cost biomass feedstocks with inferior quality (i.e., high content of unwanted components) can help decrease production costs but will result in lower production yields. A potential solution to this problem is to subject low-quality feedstocks to additional preprocessing steps aiming to minimize the negative effects of unwanted components and increase overall production yields.\textsuperscript{13}

The cost-effectiveness of biomass conversion could be increased by focusing on maximizing biomass use. This could be accomplished by expanding the product portfolio of any given biorefinery. For example, the integration of biofuel production (low-value/high-volume) with other high-value/low-volume bioproducts such as pharmaceuticals, biochemicals, biomaterials, and fertilizers can improve the economic viability of biorefineries.\textsuperscript{44} Such an approach is commonly referred to as the \textit{integrated biorefinery}. Integrated biorefineries offer more flexibility and reduced production costs by making use of side streams and wastes to produce a range of high-value and low-value bioproducts.\textsuperscript{45} It should be noted that reaching \textit{economies of scale} is a central concern for the economic success of a biorefinery and that the optimal production size depends on the type of feedstock used and processes taking place.\textsuperscript{46,47} A unique challenge in this regard involves the reality that, as a biorefinery’s production capacity increases, its processing costs decrease, but its biomass transportation costs can escalate as the biomass supply shed expands to meet the biorefinery’s need.
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Product marketing and end use stage

The final stage of the supply chain involves getting bioproducts to the market where they can be purchased and utilized by the consumers. This final stage is where the full impact of the bioeconomy on sustainability is illuminated. Depending on their end use, bioproducts can either be consumed fully during their utilization (as is the case for biofuels and bioenergy), or they can be reused within the bioeconomy supply chain, therefore resulting in a circular bioeconomy (depicted in Fig. 2). For example, bioproduct waste can be composted to promote the growth of sustainable biomass or can be utilized directly in the conversion process as a waste feedstock to produce other bioproducts (also known as cascading process). Overall, this ‘closed-loop’ approach has the potential to make the entire bioeconomy even more sustainable by promoting the use of its products’ waste as a resource. The circular bioeconomy represents a

Figure 3. Schematics showing different biomass conversion pathways to generate different bioproducts, along with their technology readiness levels (TRL). Republished with permission of the National Academies Press, from Negative Emissions Technologies and Reliable Sequestration: A Research Agenda, 2019; permission conveyed through Copyright Clearance Center, Inc.42
narrower concept than that of the bioeconomy as a whole,\textsuperscript{18} hence a full discussion of the circular bioeconomy is beyond the scope of this paper.

Despite the potential benefits of bioproducts, major hurdles to capturing market share from conventional product manufacturers remain. In addition to the advantages associated with conventional product incumbency (such as brand recognition and established distribution channels), their petroleum-based composition allows them to capture and retain market share based on price, an option thus far not widely available to bioproduct producers. One strategy for mitigating this challenge and creating a robust market for bioproducts is to ensure that customers are well informed about the various benefits of bioproducts over conventional ones. Initiatives to achieve this goal might include educating the public on the variety of biobased products they may already be using or could be using, educating the consumers on bioproducts facts and benefits, coordinating with states to promote consumer education and outreach efforts that support regional market demand, and more.\textsuperscript{23} The BioPreferred Program provides a powerful example of how government can advance these efforts, providing a USDA-certified biobased product labeling system that promotes awareness and consumption of biobased products.\textsuperscript{16}

Furthermore, the bioeconomy industry currently strikes the balance between, on the one hand, willingness to pay through increased consumer education efforts, and on the other hand, cost savings that aim to reduce the price of final products. In particular, a global survey revealed that the number of consumers willing to pay more for a product with sustainable packaging decreases as the difference in price rises. More than half of the people surveyed would either not pay more for the sustainable option or they would only pay a final price value up to 5% greater than the non-sustainable option.\textsuperscript{46} This purchasing behavior reinforces the importance of decreasing the production costs across the supply chain to make bioproducts more economically competitive with conventional alternatives. In addition to reducing costs, driving customer behavioral changes towards more sustainable choices plays a crucial role for a successful bioeconomy. It is imperative that the society as a whole embrace such changes through the adoption of more sustainable consumption behaviors and acceptance of new technologies, for example.\textsuperscript{49} Therefore, to compete on price point as well as increase market demand for biobased products, an all-hands-on-deck strategy is necessary. This strategy will need to include favorable public policies, substantial investment in R&D to lower the price of bioproducts, and significant marketing and consumer education efforts.

Public policy

As is the case in other countries (such as Germany, Ireland, Canada, and Finland), the advancement of the US bioeconomy is heavily dependent on public policy.\textsuperscript{6,50–54} In the USA, efforts focused on the development of the bioeconomy are reflected in a variety of reports, including the 2012 National Bioeconomy Blueprint, the Bioenergy Technologies Office’s (BETO’s) Strategic Plan for a Thriving and Sustainable Bioenergy, the Billion-Ton Study, and more. A range of federal agencies not only generate these critical policy documents but also play unique roles in promoting the sector. For instance, USDA frequently supports the development of feedstocks and end products and promotes the consumption of bioproducts. The United States Environmental Protection Agency (EPA) articulates national biofuel standards and regulations, whereas the National Science Foundation (NSF) supports research and development for innovative technologies necessary to the sector’s growth.\textsuperscript{9} The DOE combines the roles of different agencies (such as the Bioenergy Technologies Office, Vehicle Technologies Office, Advanced Manufacturing Office, and others) to support R&D of biomass conversion into various products through partnerships with public and private stakeholders, as well as to implement programs that support market growth, workforce development, and education.\textsuperscript{5} In general, such public policies are considered to be an intervention by the US government to mitigate climate change on behalf of the American public. These policies are indeed often crafted with a common goal: impeding climate change, promoting rural development, reducing dependence on foreign oil, and providing stable and affordable energy.\textsuperscript{6}

To achieve those goals, many policies include strict measures supporting the generation, distribution, and use of renewable energy. These policies have been adapted to meet different market conditions, available technology, and the general social environment. While many mandates were reduced or eliminated under former President Donald Trump, the new administration led by President Joe Biden has already signaled its intention to reinvigorate climate-friendly policies. Early plans include a 100% clean energy economy reaching zero emissions by 2050, a $400 billion investment in clean energy infrastructure, products, and services, a $300 billion investment in R&D across many areas (some directly related to the bioeconomy such as biotechnology and biofuels), and an entire division focused on low-carbon manufacturing.\textsuperscript{55} Two major plans directly impacting the bioeconomy include (i) investing in biofuels R&D and (ii) developing an American biobased manufacturing system that unites research communities, manufacturing institutes, and
the government. Together, these plans have the potential to create a multitude of jobs and invigorate rural development.

**Public policies within the bioeconomy supply chain**

Public policies that are tightly aligned with the different stages of the bioeconomy supply chain can further accelerate the development of the bioeconomy as a whole. Such policies can be found within three levels of governance and public management: national, state, and local. Further, relevant policies can be described as either incentive-based (for example, subsidies and tax credits), market-based (for instance, imposing regulations that directly intervene with the market), or information-based (for example, flyers, labels, booklets, training, and websites). Certain policies can also be categorized according to the stages of the bioeconomy supply chain that they address. Regardless of targeted areas, each of the various policy types has its unique role in promoting the growth of the bioeconomy across the entirety of the supply chain.

**Public policies targeting biomass production**

Targeting the first stage of the supply chain, the Biomass Crop Assistance Program has been particularly effective. The program was created through the Food, Conservation, and Energy Act of 2008, which was a continuation of the 2002 Farm Bill, as part of a federal strategy focused on decreasing foreign dependence on oil, increasing energy security, and reducing GHG emissions. The main objective of the program is to provide financial assistance to agricultural and forest landowners to incentivize the production of biomass feedstock for bioenergy purposes. Such incentives are important tools for overcoming challenges associated with biomass scarcity. The Biomass Crop Assistance program has the potential to increase biomass supply and production by over 60%, which would have dramatic downstream impacts on the supply chain.

**Public policies targeting conversion process and product manufacturing**

Public policies targeting the second stage of the supply are primarily associated with the production of bioenergy to be used in the transportation and power sectors. These two sectors are more visible to the general public because they are not only the fastest growing sectors in the USA but also are responsible for over half of the emissions in the country. Accordingly, several important policies, including the Renewable Fuel Standard (RFS), the California Low Carbon Fuel Standard (LCFS), and the Renewable Portfolio Standards (RPS) are currently implemented across the USA.

The Renewable Fuel Standard (RFS) is a federal regulatory-based mandate created under the 2005 Energy Policy Act and later revised by the 2007 Energy Independence and Security Act as RFS2. The RFS was created to encourage the use of renewable fuels while decreasing US dependence on foreign oil. In addition to mandating the annual volume of biofuels used within the transportation sector, the RFS specifies that all renewable fuels must also have a lifecycle GHG emissions level equal to or below a baseline established by the EPA. The RFS also expanded the market for biofuels through the creation of a national Renewable Identification Number (RIN) system. Renewable Identification Numbers play a part in subsidizing biofuels and increasing the cost of petroleum fuels (gasoline and diesel).

The California Low Carbon Fuel Standard (LCFS) provides another example of a successful transportation-related policy. As one of the largest consumers of transportation fuel in the nation, California represents 11% of all gasoline and 8% of all diesel consumption in the United States. Given the magnitude of the state's fuel consumption and the fact that Californians as a whole tend to support pro-environment issues, it is no surprise that the state's LCFS provides an exemplary bioeconomy policy. The LCFS was, in fact, created through the state's 32nd Assembly Bill to reduce GHG emissions and incentivize biofuel technological development. In contrast to the national RFS, the LCFS establishes a baseline carbon intensity (CI) level using life cycle analysis for all types of transportation fuels, rather than mandating annual biofuel volumes. Any fuels with a CI higher than the baseline result in deficit ratings that require companies to generate credits equal to or greater than the deficit. Credits can be accumulated by selling fuels with a CI below the baseline. Such credits are then traded within the LCFS marketplace. Newer policies (such as British Columbia's Renewable and Low Carbon Fuel Requirement Regulation, and Oregon's Clean Fuels Program) have followed California's lead, crafting their standards and incentive structures after the LCFS. This suggests that the LCFS has had a broad impact beyond California.

In the biopower sector, the Renewable Portfolio Standards (RPS) incentivizes the use of renewable resources (such as solar, wind, and biomass) for electricity production. Like the LCFS, the RPS are a state-level regulatory policy. The majority of RPS-related renewable energy capacity additions between 2013 and 2014 were from solar and wind (64% combined), whereas biomass contributed only 4%. This discrepancy can be attributed to the higher cost of power generation from biomass relative to solar and wind. Given this cost differential, most biomass is used in the production of biofuels rather than power. At the federal level, the...
Producers Tax Credit (PTC) and the Investment Tax Credit (ITC) provide energy producers and investors with financial incentives to overcome the significant economic barrier associated with capital costs.\textsuperscript{70,74} Both PTC and ITC target relatively small-scale projects, perhaps as a way to encourage market newcomers.\textsuperscript{72,73}

Public policies targeting product marketing

The policy most famously associated with the third and final stage of the supply chain is the national BioPreferred Program. The BioPreferred Program was created through the 2002 Farm Bill legislation and expanded under the 2014 Farm Bill. Its implementation is overseen by the USDA. With its pivotal role in marketing bioproducts, the BioPreferred Program allows companies to apply for biobased certification by submitting evidence of product composition to the USDA and the American Society for Testing and Materials (ASTM).\textsuperscript{16} Upon accreditation, a label attesting to the product’s biobased origin and the percentage of its biobased content can be applied to packaging. With its goal of promoting economic development by expanding the market for biobased products, the BioPreferred program has resulted in 2500 products in 100 categories being accredited.\textsuperscript{16} Along with the Biobased Program, the Farm Bill requires federal agencies and contractors to purchase bioproducts (such as cleaning supplies, carpets, paints, and more). The BioPreferred Program furthers this effort by providing information resources such as catalogs to ensure that purchased products comply with the Bill’s guidelines.\textsuperscript{16} Since 2005, product categories for this program have grown from just six to over 90, and more than 10 000 different kinds of USDA-labeled products are available in the market today.

Policy efforts towards developing the bioeconomy’s potential

Growing the bioeconomy to achieve its full potential is a daunting task, especially when conventional and cheaper alternatives dominate the market. Gasoline, coal, and natural gas industries have staved off competition, enjoyed substantial investments, and benefitted from a favorable regulatory environment for decades.\textsuperscript{74,75} Unsurprisingly, economic barriers to entry and economies of scale are the most challenging obstacles that bioeconomy newcomers face.\textsuperscript{56,76} For this reason, policies must continue to center the idea that sustainability and economic growth go hand in hand to create a favorable environment for new market entrants and to incentivize incumbents to seek out biobased alternatives. Policymakers thus play a key role by fostering steady demand, stoking free-market competition, and galvanizing overall industry growth.\textsuperscript{56,77,78} These mutually inflecting dimensions of market growth necessitate a combination of policies that share the same goals. Such an approach will ultimately be more effective than any single policy operating in isolation.\textsuperscript{56}

When programs are strategically leveraged against each other and new policies are developed within the framework of a larger strategic plan, their efficiency and efficacy increase. For example, promising results have been found when the RPS has operated in concert with PTC and/or ITC.\textsuperscript{72} The RPS focuses on encouraging the use of renewable energy, while the PTC and ITC reduce its cost through tax incentives. Together, these policy instruments increase the competitive position of renewable energy vis-à-vis fossil options. Transportation-related policies have also proven particularly effective. For example, the RFS mandates guarantees a steady demand in the corn ethanol industry, exerting a positive influence on ethanol production economies of scale. This, in turn, led to an increase in capacity expansion.\textsuperscript{77} In the case of the LCFS, a 21% decrease in average carbon intensity and a 30% increase in alternative fuel consumption was realized between 2011 and 2015.\textsuperscript{56,79} Several studies have suggested that the underlying success of these policies is attributable to the fact that they work alongside each other, ultimately generating both higher demand and lower GHG emissions.\textsuperscript{77,80,81}

Policies that are well designed, coordinated, and effectively implemented have broader economic impacts. Resulting in economic development and job creation, such policies tend to gain popularity, creating a positive feedback loop overall. The RPS, for example, has endured over many years, largely because it led to significant economic growth within the bioeconomy.\textsuperscript{68} The contribution of biomass power and capacity from the RPS added 8300 construction and 3300 operations and maintenance jobs.\textsuperscript{67,82} Similarly, the ethanol industry added over 383 000 jobs (26% direct, 22% indirect, and 52% induced) and $43 billion to the US economy in 2012 alone.\textsuperscript{83} In 2013, the bioproducts industry directly contributed $126 billion and 1.52 million jobs to the US economy with the support of the BioPreferred Program, and the indirect contributions amplified these numbers to $369 billion and roughly 4 million jobs. Such results are a testament to the efficacy of cohesive policies and a programmatic approach.\textsuperscript{84}

Public policy serves not only as an important industry regulator but also an important driver of the bioeconomy. To drive progress forward, it is equally important to dedicate policy efforts towards the education of a community that understands both the advantages and the necessity of a healthy bioeconomy. Yet, social barriers (such as the lack of public awareness and a shortage of experienced professionals), along with economic, technological, and regulatory barriers, remain significant.\textsuperscript{85} To address this
challenge, policymakers would be well-advised to develop a robust and intentional education platform specifically for the bioeconomy sector. Such a platform must target not only the future workforce but also consumers, stakeholders, and policymakers because targeting these groups simultaneously instead of individually will result in synergistic effects. Moreover, education efforts for workforce development must be shaped including not only members of the higher education community where current efforts are concentrated, but across the entirety of the childhood-to-career pipeline.

**Education**

**Education overview in the USA: Federal, state, and local**

Public awareness and education related to the bioeconomy are key to developing a well prepared workforce. In designing a comprehensive strategy for bioenergy education, it is important to recognize that education in the USA is a decentralized phenomenon. In the post-secondary context, colleges and universities operate under a faculty governance structure, with academic units overseeing curricular decisions that shape what knowledge and skills students must acquire. Of course, there are various levels of review and checks and balances, but overall, each institution of higher education has high levels of autonomy in terms of curricular decisions. On the other hand, the context from pre-kindergarten to high school is shaped by some degree of self-governance, although this is more variable and regulated, including a system of professional licensure.

In the latter context, the ultimate responsibility for determining what students will learn falls on each of the 50 states, and, in many instances, on local school districts. At the state level, boards of education create metrics to establish consistency and performance expectations. Model curricular standards are developed at the federal level and are offered to states as guidance but each state develops its own core curricula. State and local sources provide the biggest share of funding for public education. In 2018, for example, the federal government contributed 7.7%, whereas state governments provided 46.7%, and the local governments contributed 45.6%. A robust ecosystem of informal education (often through community organizations and nonprofit entities) often complements the curricular content students experience in schools.

**K – 12 education**

Preparing US students at the K-12 level to enter the bioeconomy workforce successfully is very important. For instance, a study found that US primary and secondary students across all grade bands lack core knowledge about biologically based energy sources. The authors argued that this lack of knowledge will inevitably impact students’ ability to make informed decisions as consumers regarding alternative energy sources in the future. This is a remarkably low bar. If students are unable to make informed decisions when choosing among energy sources in their daily lives, it is unlikely they will be positioned to make intentional, strategic decisions related to following bioeconomy career paths, let alone make significant contributions if they happen to find themselves in that arena. To better understand the high stakes associated with providing K-12 students with the knowledge and skills needed to participate meaningfully in the bioeconomy workforce, it is useful to consult with current bioeconomy leaders. Experts within the field have identified several ‘high-priority’ bioenergy concept themes for K-12 students, as summarized in Table 2.

Interestingly, a review of the Next Generation Science Standards (NGSS), which guide many state science content standards, reveals that these topics and themes are indeed being addressed by education leaders. However, while the standards appear to address thoroughly foundational knowledge and the necessary skills to thrive in the bioeconomy, a search through the NGSS database for the term ‘bioeconomy’ did not return any results (but multiple mentions were obtained when searching the database for the related term ‘biomass’). Therefore, while topics related to the

| Theme | Field |
|-------|-------|
| Energy requirements: Quantity and type of energy needed | Engineering |
| Energy consumption: Current and historical energy sources | Engineering |
| Climate change: Historical record and projected consequences | Science |
| Nature of engineering: How engineering is important to bioenergy | Engineering |
| Energy fundamentals: Work, energy, conversions | Engineering |
| Life cycle assessment: Environmental impacts cradle to grave | Science |
| Photosynthesis: How light energy is stored in plants | Science |
| Conversion principles: Type of biomass conversions | Science |
| Chemical cycles: Water, carbon, nitrogen cycles | Science |
| Ecosystems: Ecology and human impact | Science |

Table 2. Survey responses regarding priority themes (bioenergy engineering and science) recognized by experts for K-12 education.
bioeconomy are indeed addressed through the NGSS, the lack of explicitness related to the bioeconomy itself is an issue. Hence, the combined focus on foundational knowledge and lack of bioeconomy specificity represents an opportunity. The standards are organized into three key areas of focus: (i) science and engineering practices, (ii) disciplinary core ideas, and (iii) crosscutting concepts. The science and engineering practices help to describe how scientists and engineers do their jobs. Disciplinary core ideas (DCIs) are considered ‘key ideas’ that are essential either for one discipline or across many disciplines, and are further classified into four areas: Physical science, life science, earth and space sciences, and engineering. Crosscutting concepts are presented from an interdisciplinary perspective, intending to support educators in facilitating student’s explorations of big ideas that connect the four areas.

The concept of ‘bioeconomy’ could quite logically be introduced within high school-level science education under the earth and space sciences DCI subject of human sustainability, for example. Here, students could learn about the bioeconomy as they explore ways to ‘evaluate or refine a technological solution that reduces impacts of human activities on natural systems.’ At the middle-school level, the earth and space sciences DCI includes a human impacts subcategory where students could explore the bioeconomy when they ‘apply scientific principles to design a method for monitoring and minimizing a human impact on the environment.’ Finally, in elementary schools, the concept could be easily introduced at the kindergarten and third-grade levels when they study ‘interdependent relationships in ecosystems: Animals, plants, and their environment.’ A similar opportunity exists for second graders studying ‘interdependent relationships in ecosystems.’ Clearly, K-12 students would benefit dramatically if the bioeconomy were introduced, and NGSS provides multiple opportunities to do so. In addition to providing robust theme-based learning, incorporating the bioeconomy as a well-defined concept would allow students to develop mental models of what this vast sector is and how they might find their place within it.

Postsecondary education: Undergraduate

As noted above, an interdisciplinary workforce across the entirety of the supply chain is critical to the success of the bioeconomy. This requires capable professionals with expertise in a range of areas such as engineering, science, biotechnology, business, finance, agriculture, policy, marketing, and many other fields. Yet, in the USA, postsecondary education efforts relevant to the bioeconomy focus primarily on technological advancement through science, technology, engineering, and mathematics (STEM) specializations. Academic programs such as computing, engineering, biology, synthetic biology, bioprocessing, and biotechnology tend to provide the most explicit pathways to bioeconomy related training. Nonetheless, the narrow scope of most postsecondary programs like these can present a barrier to preparing professionals who are simultaneously specialists and well rounded, interdisciplinary thinkers with a broad-based understanding of the most pressing issues addressed within the bioeconomy.

For students exploring careers in bioeconomy industries, understanding the sector’s complexity is critically important. Its complexity inherently requires strong interdisciplinary knowledge and skills, yet many students simply do not possess the interdisciplinary knowledge that is needed to succeed within and advance the bioeconomy. In this context, interdisciplinary knowledge and skills involve integrative abilities and collaboration competencies that enable individuals to work effectively across multiple disciplines and develop contextualized solutions to problems. Integrated-type programs that combine a range of disciplinary perspectives are therefore key to the development of a capable bioeconomy workforce. A previous study identified 13 essential components of a postsecondary level curriculum related to bioenergy, including energy basics, types of bioenergy, environmental impacts (including life cycle analysis), current technologies, societal issues, logistics, policy, biomass composition, non-bioenergy-specific fundamentals, biomass production, conversions, bioenergy market, and business-related knowledge.

It should be noted that some institutions of higher education do have their own bioeconomy education initiatives with programs designed from an interdisciplinary perspective. Solano Community College, for example, has an integrated-type program in which students are required to take both science and a range of classes in other subject areas, including business and public policy pertaining to biotechnology. At North Carolina State University, the Sustainable Bioproducts and Bioenergy Program (funded by the USDA) created a collaboration between the Colleges of Natural Resources and of Education. The program focuses on providing bioeconomy-related professional development to in-service science teachers in rural high school communities through lesson plans, workshops, and coursework on renewable resources. The ultimate goal of this program is to support high-school students in constructing knowledge and developing skills that eventually lead to them making meaningful discoveries within the bioeconomy. Furthermore, it is of great value that the future workforce learns from real-world scenarios related to the bioeconomy.
For instance, as with any new industry, there have been biofuel commercialization efforts that failed, resulting in substantial losses. These failures provide excellent case studies for undergraduate capstone design classes and graduate courses examining the emerging biosource industry. Issues such as project financing, government support, technical challenges and mistakes, and the fallout from the project failure are often discussed in post mortem articles. These case studies provide students with a real-world perspective on the challenges in starting a new industry and will serve them well as they become the future industry leaders.

Postsecondary education: Graduate

There are many graduate programs offered throughout the USA that focus on sustainable energy, sustainability, or other related areas, but there are a limited number of institutions that have research programs focused solely on the bioeconomy. One such institution is the University of Arizona, which offers a professional science master's degree in the applied biosciences with a sustainable bioeconomy and bioenergy emphasis. This program is broadly conceptualized and covers everything from feedstock selection to sustainable feedstock production, conversion from feedstock to biofuels, bioenergy, and value-added products. The curriculum also supports students in quantifying the technical, economic, and sustainability impacts of bioenergy pathways through its focus on techno-economic analysis and sustainability models.92

At Pennsylvania State University, the College of Agricultural Sciences offers several graduate degrees related to the bioeconomy.93 One such program (agricultural and biological engineering) allows students to undertake a range of research projects related to renewable biofuels, bioproducts development, synthetic biological engineering, biological and food process engineering, biosensors and instrumentation, natural resources engineering for sustainability of water and land use, and more. The college also offers a biorenewable systems graduate program, which represents an interdisciplinary approach that combines bioeconomy-related science, technology, and business content. This program focuses on biobased products and materials as well as business aspects, including supply-chain management, entrepreneurship, marketing, general management, and leadership. Finally, the college also offers the following graduate programs that are also directly related to the bioeconomy: Agricultural and environmental plant science, agricultural and extension education, forest resources, plant pathology, rural sociology, and soil science.93

It is clear that graduate programs explicitly focused on the bioeconomy are relatively rare, but there are many more opportunities to engage with the content at the graduate, rather than undergraduate and K-12 levels. Indeed, the USA is one of the leading countries in terms of bioeconomy-related scientific output originating in higher education. According to the NSF, in 2016 alone, the USA generated 73,208 academic publications related to the biological sciences, second only to the European Union (92,066 publications).6

Informal education efforts

The education efforts explored up to this point (K-12 and postsecondary education) are commonly referred to as ‘formal education’. However, there are significant informal bioeconomy-related educational efforts across the country. For instance, since 2015, agencies such as BETO, the USDA, and NREL, have facilitated more than 20 out-of-school workshops related to the bioeconomy for students and/or their educators.94 These workshops have covered a range of topics, including biofuels and biochemicals production, biomass feedstock production and logistics, synthetic biology, integrated biorefineries, and more. The Bioenergy Technologies Office has also developed a Bioenergy Career Map, an online interactive tool that allows its users to discover current and future opportunities within the US bioeconomy by presenting information in an accessible and practical way.25

Another important initiative is one that is near and dear to the authors of this paper. The Consortium for Advanced Bioeconomy Leadership Education (CABLE) is overseen by The Ohio State University and includes 21 partner universities nationwide as well as dozens of industry partners.95 It is supported by funding through the USDA-NIFA and, over the course of its 4 year history, has educated a total of 57 university-level students (29 graduate and 28 undergraduate) from different areas and majors relevant to the bioeconomy. Cohorts of promising students undergo a year of leadership training and learn about the different areas of the bioeconomy through inter-university research projects (including biomass supply, public policy, green transportation, biobased products, and industry case studies), public outreach events, and industry conferences. Many of the participants (including several authors of this review) learned about the bioeconomy for the first time through this program, despite pursuing directly relevant areas of study, and several program alumni have deliberately embarked on careers in the bioeconomy as a direct result of their participation in CABLE. Thus, we are uniquely positioned to attest to the power of bioeconomy education on young people's career choices. When an external evaluator asked participants about the value of the program, many responses focused on the importance of combining leadership training, networking opportunities,
exposure to industry, teamwork, personal growth, and a sense of community with developing core knowledge about the bioeconomy. Through our first-hand experience, we cannot overstate the importance of increasing educational efforts directly addressing the bioeconomy in order to engage, energize, and train its future workforce.

Concluding remarks

The success of the bioeconomy relies on stakeholders viewing it from a holistic point of view and perceiving it as a system consisting of individual parts that must advance together rather than separately. Hence, this article presented a comprehensive view of the US bioeconomy by showing intersections in three key areas: industry, public policy, and education. The synergistic effect of a robust industrial marketplace, the force of engaged policymakers, an educated workforce, and a broad base of well-informed consumers is what we need to rapidly move a thriving bioeconomy forward and create a more sustainable world for future generations. The authors realized that education is the central piece for achieving this synergy. Education efforts should therefore be transdisciplinary (that is, directed not only to academic but also actively engaged non-academic stakeholders) to develop the bioeconomy in a balanced manner and overcome current gaps in the system. Furthermore, it is clear that public policy serves as an important industry regulator and an essential driver of the bioeconomy, but many policymakers are not aware of the bioeconomy. Educating policymakers about the bioeconomy’s full potential can result in the creation of policies that favor sustainability and economic growth by reducing investment uncertainties for new market entrants. Educating the general public to recognize easily the environmental benefits and high level of performance of biobased products can increase their interest in more sustainable alternatives. As for the future workforce, education initiatives must simultaneously focus on specialized, STEM-oriented curricula as well as broad-based, interdisciplinary skills and perspectives. There also needs to be an intentional effort on a bioeconomy education that begins in the early years of schooling and continues into higher education. As a result of these efforts, the bioeconomy will have knowledgeable, skilled, multi-talented professionals who understand how the system works and can work collaboratively towards collective goals. Altogether, advancing the different areas of the bioeconomy (including industry, public policy, and education) in a coordinated and holistic manner will result in the growth of the bioeconomy, which will generate environmental, social, and economic benefits across the nation.

Acknowledgements

This work was sponsored by the Consortium for Advanced Bioeconomy Leadership Education (CABLE), a nationwide organization supported by the United States Department of Agriculture, National Institute of Food and Agriculture (USDA-NIFA) Competitive Grant no. 2017-6700-926770. The authors are grateful to the CABLE executive management members, especially to Principal Investigator Dennis Hall, and Zia Chadzynska, Melinda Lloyd, Richard ‘Max’ Maksimowski, and Corinne Rutzke for their constant support and guidance across the 4 years of the program.

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Danielle U. Pascoli

Danielle U. Pascoli is currently a PhD student at the University of Washington. She holds a bachelor of science degree in biochemical engineering from the University of São Paulo, Brazil, and a master of science degree in bioresource science and engineering from the University of Washington. Her primary research interest is the conversion of lignocellulosic biomass into biofuels, biomaterials, and biochemicals, with an emphasis on process development and techno-economic analysis. Her current research project focuses on developing a sustainable process to convert low-cost biomass feedstocks into high-value nanocellulose materials. Danielle has also participated in the Consortium for Advanced Bioeconomy Leadership Education (CABLE) program since 2019, alongside the co-authors of this manuscript.

Alvina Aui

Alvina Aui is finishing her PhD dissertation on bio-energy systems from an economic, environmental, and public policy perspective at Iowa State University. Her research interests are techno-economics, life-cycle analysis, uncertainty quantification, meta-analyses, and statistical analyses. She has worked on various projects, including waste-to-power anaerobic digestion energy system, thermochemical conversion of biomass to fuels, and biofuel policy analysis.

Jenny Frank

Jenny Frank is a PhD candidate at the State University of New York College of Environmental Science and Forestry (SUNY ESF). She specializes in techno-economic analysis (TEA) for renewable energy pathways, with a focus on bioenergy.

Obste Therasme

Obste Therasme is an assistant professor in the Department of Sustainable Resources Management at SUNY ESF. His research interests include life-cycle assessment (LCA) of energy systems and novel products, analysis of net zero/negative greenhouse gas emissions systems, and conversion of biomass for biofuels, energy, and bioproducts. He holds a PhD in sustainable energy from SUNY ESF, a master of science degree in chemical engineering from Syracuse University, and a bachelor's degree in chemistry from the State University of Haiti.
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Rick Gustafson
Rick Gustafson holds the Denman Chair of Bioresource Science and Engineering in the School of Environmental and Forest Sciences at the University of Washington. Professor Gustafson's research interest includes the development of integrated biorefineries that produce a range of products (from commodity fuels to high value food additives) from renewable biomass. The processes he develops integrates biomass production with conversion processes to enable enterprises that are economically viable and that have substantial environmental benefits. His research focuses on applying fundamental research to process simulations that are used in economic assessments to determine financial viability and in life-cycle assessments to evaluate the broad environmental impact of candidate process configurations.

Brendan Kelly
Dr Brendan Kelly is an assistant professor in the Department of Plant and Soil Science at Texas Tech University. He holds a joint appointment with Texas A&M AgriLife Research Institute in Lubbock, Texas, and focuses on developing phenotyping tools and germplasm improvement techniques needed for crop quality improvement. The application of techniques developed in his laboratory requires collaboration with traditional breeders and plant biotechnologists and has led to the development of cotton (Gossypium hirsutum) germplasm with an improved fiber quality profile, which is more competitive on international spinning markets.

Kerry Dixon
Kerry Dixon is the executive director of Beta by Design, a nonprofit organization that advances research-based understanding of interdisciplinary teaching and learning, with a particular focus on assessing large-scale, multi-partner, cross-sector initiatives. As an external evaluator for multiple projects, including the Consortium for Advanced Bioeconomy Leadership Education (CABLE), Dr Dixon oversees the design of comprehensive evaluation plans, formative and summative assessments, data-driven continuous improvement plans, sustainable business model designs, financial modeling, and reporting. She has extensive experience in higher education (teaching, research, and administration) as well as K-12 formal and informal education. Dr Dixon's research focuses on the phenomenon of interdisciplinarity in highly matrixed organizations, especially in the education and public management sectors. All of her work is conducted using critical multicultural and equity-based theoretical frameworks. Dr Dixon holds a PhD in education from the Ohio State University, a master's degree from the University of Chicago where she was a Century Scholar, and a bachelor's degree from Bates College. She is currently completing an MBA at the Ohio State University.

Timothy A. Volk
Dr Timothy Volk is a professor in the Department of Sustainable Resources Management at SUNY ESF. His research focuses on the development of shrub willow biomass cropping systems as a feedstock for bioproducts and bioenergy, sustainability assessments of bioenergy systems, phytoremediation, and agroforestry.

Brendan Kelly
Dr Mark M. Wright is an associate professor in mechanical engineering at Iowa State University. His research interests are in the development and evaluation of biomass conversion technologies using techno-economic analysis, life-cycle assessment, and uncertainty quantification.