THE ONCE AND FUTURE BIOECONOMY AND THE ROLE OF FORESTS

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Executive Summary

There are increasing references in popular and scientific literature to an emerging "bioeconomy." But what is meant by this term, and what does it imply for the near and longer term future? Part of the answer is revealed by the past.

From the beginning of European settlement of North America through the beginning of the 20th century, citizens relied heavily on wood and agricultural crops to provide food, shelter, energy, transportation, clothing, and other products of all kinds. In other words, the economy was based on materials and products made from once living things (i.e. biomaterials). Agriculture yielded not only food, but flax, wool, hides, cotton, and hemp used to make clothing, canvas, cordage, and leather. Wood was the mainstay of ships, buggies and wagons (and later automobiles), homes and buildings of commerce, bridges and sidewalks, buckets and barrels, implements, utensils, newsprint and books, fencing, and more. Wood was also the primary source of energy until the late 1800s. Even ethanol, which is used as a fuel today, was produced from agricultural crops as long ago as the late 1800s.

Over time, society increasingly turned to metals for production of vehicles and ships, and to steel and concrete for construction of buildings of commerce. Steel and concrete also became materials of choice for construction of houses and apartment buildings in Europe, much of Asia, and the Middle East. Similarly, fossil-fuel-based fibers such as nylon, polyester, and acrylic replaced natural fiber in a number of applications. Plastics, derived from fossil fuels, found increasing uses beginning in the late 1920s. Energy markets became dominated by fossil fuels, and the rise of electronics was fueled by a wide array of relatively scarce and high environmental impact metals. Today, wood and non-food agricultural products continue to be used in large volumes, though plant-based materials don't dominate commerce as they once did.

But a quiet revolution is underway. Based in part on rising environmental and social concerns linked to fossil fuel consumption and heavy reliance on non-renewable materials, development of new families of renewable, low impact and plant-based materials and products of all kinds is taking place in laboratories around the world. Some are already on the market, while others are in concept or developmental stages. Success to date suggests that such materials and products will become common in the future, in the process causing a significant shift back toward an economy based on biological materials. Although a return to near total reliance on biomaterials, as in the late 1800s, is not envisioned, the magnitude of expected developments are sufficient to inspire references to a coming bio-based economy.

The Past as Future

To some, renewal of interest in bio-resources (resources derived from plants or animals) signals a revolution in social thinking. Visionary David Morris briefly outlined the history and future of reliance on biomaterials in the United States in the fascinating article "The Once and Future Carbohydrate Economy." In it he says in part:

Less than 200 years ago, industrializing societies were carbohydrate economies. In 1820, Americans used two tons of vegetables for every one ton of minerals. Plants were the primary raw material in the production of dyes, chemicals, paints, inks, solvents, construction materials, even energy. . . Then we shifted to a fossil-fuel based economy based on low crude oil prices. By

1920 the nation had reversed the vegetable-mineral ratio, using two tons of minerals for every one ton of vegetables.

In the early history of the United States, bio-products were everywhere in evidence, as illustrated in artists sketches and photographs of preserved buildings and artifacts from the colonial era (Figures 1, 2). Encountering vast forests, early settlers used wood for virtually everything. Buildings and furniture, spinning wheels and looms, dishes and pails, wagons and carriages, boats and ships, bridges and sidewalks, plows and hay rakes, milling machinery and sawmills, and products of every kind and shape were made of wood. Wood was also used for heating and cooking and as the principal fuel of industry. Agriculture provided not only food, but leather, and flax, wool, cotton, and hemp used to make clothing, canvas, and cordage. The entire economy was bio-based.

Figure 1
Prolific Use of Wood in Colonial America

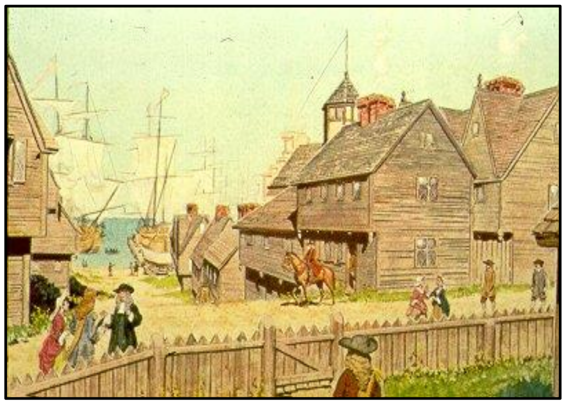
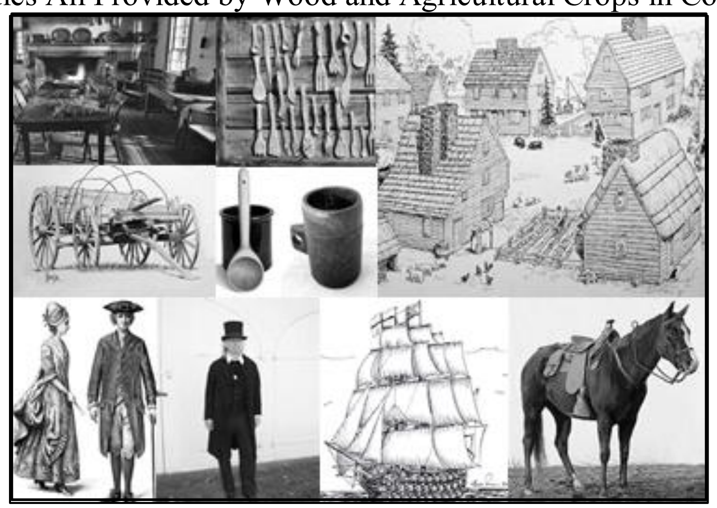


Figure 2
Furniture, Home Heating, Utensils, Cups, Buildings, Wagons, Ships, Ship Canvas and Cording, Clothing, Saddles All Provided by Wood and Agricultural Crops in Colonial America



Reliance on biomaterials waned toward the end of the 19th century as steel and concrete became the primary structural materials for construction of large buildings in North America and as fossil fuels displaced wood as an energy source. While steel also began to be used for vehicle frames, bodies, and wheels, replacing wood and canvas in production of vehicles, biomaterials nonetheless remained prominent in the early automobile industry well into the 20th century. For instance, the body, undercarriage, wheel rims and spokes of the 1901 curved-dash Oldsmobile (Figure 3) were all made of wood. The tires were natural rubber.

Eight years later the Ford touring car retained many of the same characteristics: wood undercarriage and body, wood wheels and spokes, canvas top, and natural rubber tires. Moreover, the engine was designed to run on gasoline, kerosene, or ethanol.

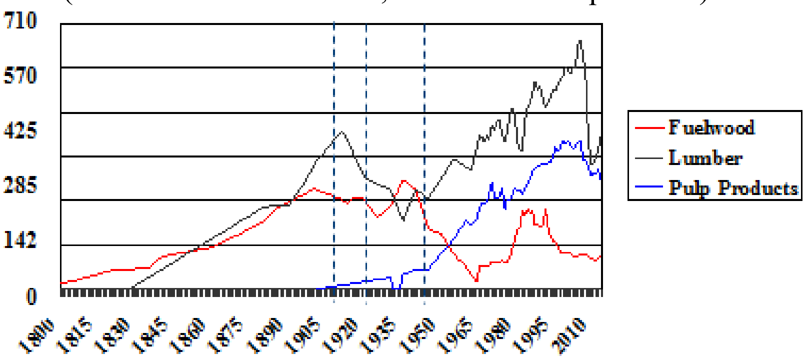
Figure 3
Bio-products were Prominent in Early Automobiles

Curved-dash Oldsmobile 1901

1909 Ford Touring Car

Growth in energy consumption after the late 1800s was largely accommodated by fossil fuels, leading to a decline in the use of wood fuels early in the 20th century. Lumber production also began to decline a few years later, with these trends clearly marking the end of the early bio-based economy (Figure 4). Although use of wood for energy reached a new high in the course of the Great Depression, 1929-1931, the nation's energy needs were overwhelmingly provided by fossil fuels at this point.

Figure 4
U.S. Consumption of Wood and Wood Products, 1800-2013
(Thousand Cubic Meters, Roundwood Equivalent)



Source: Frederick and Sedjo (1991); Howard and Westby (2015)

A growing economy at mid-century marked the beginning of a resurgence of wood use as homebuilding proceeded at a rapid pace, and as use of paper and paperboard for communication, packaging, and tissue grew rapidly. By the late 1960s, wood consumption within the United States had surpassed the early 20th century peak. Then the oil shocks of the 1970s spurred interest in development of alternative forms of energy. The result was a shift to use of wood energy within the domestic forest products industry, and considerable investment in alternative fuels research, including efforts focused on agriculturally and forest-derived biofuels. Investigation of alternative sources of chemicals and industrial feedstocks obtained from fossil fuels was also undertaken, with efforts centered on agricultural crops, crop residues, and forest biomass. Meanwhile, research and development on a number of fronts examined possibilities for more efficient use of wood, inspired by concerns about rising wood consumption and declining log sizes, and thus a desire to use wood more efficiently. The sum of these actions set the stage for what many now see as the dawn of a new bioeconomy, in which an increasing portion of society's needs will be provided by renewable biomaterials and bio-products.

Research Successes Pave the Way

Changing perspectives were driven by a series of successes in research and development over a long period of time which collectively served to widen the range of possibilities for and utility of bio-based products. Developments in the areas of composite products, energy, and biochemicals are particularly notable.

<u>Wood-Based Composite Products</u>

Veneering and plywood date back to 2600-2700 BC, so it could be said that this point in time marked the beginning of wood composites. The first structural wood composites were developed in Europe in the late 1800s in response to small average timber sizes in forests which had been severely depleted over previous centuries, often a result of heavy reliance on wood fuel. The first recorded use of a structural composite in a building was the use of glue-laminated timber in construction of an auditorium in Basel, Switzerland in 1893. Although the use of non-waterproof glues in this product limited its application, the use of wood of small sizes to create large size timbers was nonetheless demonstrated. Plywood was commercially produced as a structural product, in the United States, twelve years later.

The 20th century marked rapid development of wood-based composites, with efforts largely centered in North America. Key to this development was the introduction of synthetic, highly water resistant, thermosetting resins. Phenol-formaldehyde was the first of the synthetic resins to be introduced, this in 1909. Development of urea-formaldehyde, resorcinol-formaldehyde, and melamine-formaldehyde followed soon thereafter. The original application of phenol formaldehyde was in production of electrical insulators, and use as an adhesive was not originally envisioned. However, by the early 1920s, experimentation was beginning to focus on its adhesive potential. Another 20 years would pass before use of thermosets in wood adhesion became common.

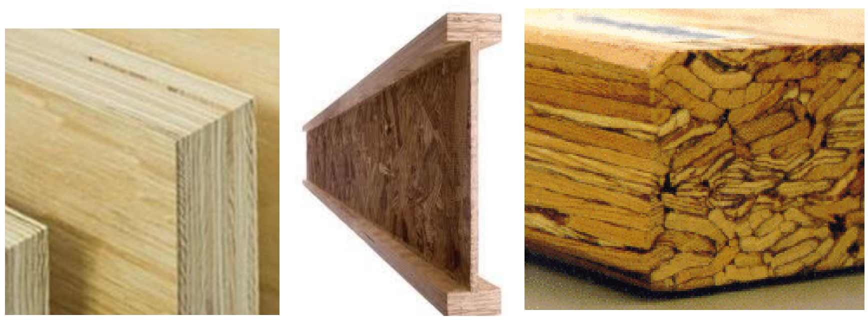
The availability of the new types of adhesives stimulated interest in new types of products that might be made using them. In the late 1930s prototype particleboard panels were made in a laboratory in Germany which led to construction of the first commercial particleboard plant there in 1941. Large scale commercial development of particleboard began in the U.S. in 1955. Applications included a range of nonstructural products including kitchen and sound system/TV cabinets, home and office furniture, and mobile home decking and carpet underlayment.

Thinking then turned to the possibility of producing structural particleboard – a product that could be used in the same ways as plywood. Research dedicated to this possibility resulted in a U.S. patent for oriented strandboard (OSB) in 1968.

Some scientists also began to consider whether the concept of glue-laminated beams and timbers, in which wood of relatively small dimensions could be fashioned into structural members of much larger size, might be expanded to include a wider range of wood components. This kind of thinking led to a myriad of possibilities.

In 1968 a U.S. patent was issued for laminated veneer lumber (LVL). This product concept not only allowed production of large wood members from relatively thin wood veneers, but also resulted in dispersal of knots and grain variation which resulted in much more uniform strength properties than solid timbers of the same wood species. In 1971, wood structural I-joists were patented; this product used vastly less wood than beams of solid wood, but also brought greater uniformity in strength properties.

Figure 5
Laminated Veneer Lumber, Structural I-Joists, and Parallam



By the mid-1980s Wood structural I-beams and LVL were both being sold on the commercial market in the U.S. Another new product, Parallam, made of long parallel strands of wood bonded into sizes typical of lumber and large beams, was also on the market (Figure5). In addition, in 1985 a patent for yet another new product concept was issued in France, wherein layers of full sized pieces of lumber would be assembled with alternating grain layers, similar to the way in which veneer sheets are arranged to produce plywood, into large, thick panels. This new product was referred to as cross laminated timber (CLT).

By the early 1990s another new composite, laminated strand lumber (LSL), was also commercially available. Within a few more years, a wood polymer composite, made from 100% recycled polyethylene and wood waste was commercially available for landscaping, outdoor furniture, and miscellaneous product applications. Wood/plastic blends were also commonly used in making molded parts for automobiles.

To many within the forest sector, the rapid fire development of new structural wood composites served only to pit one segment of the industry against another, with no real gain for the sector as a whole. However, the commercial introduction of CLT, first into European markets, and then into North America and elsewhere, brought the significance of structural wood composites development into focus. For the first time, the existence of wood members with uniform properties, that could be produced in virtually any size desired from the wood of relatively small-diameter trees, and which in large sizes offered superior fire performance than steel, created possibilities for replacing concrete and steel in construction of tall structures. Moreover, application of life cycle assessment to evaluation of buildings beginning in the mid-1990s, had clearly demonstrated that wood was environmentally better than either steel or concrete across a wide array of performance measures. What followed was nothing short of a revolution – a revolution that continues to gain momentum.

First, development of new types of engineered wood products significantly increased design options for wood structures. These developments, coupled with interest in more economical construction, led to an increase in the number of 4 to 5-story wood-framed buildings in North America around the turn of the 21st century, a trend that continues today. Second, the introduction of CLT dramatically increased the height potential for modern wood buildings.

Figure 6
Brock Commons, University of British Columbia

Source: University of British Columbia (2017)

Unthinkable only a few short years ago, the shift in possibilities for wood is exemplified by the 18-story Brock Commons building on the University of British Columbia campus in Vancouver, B.C. (Figure 6). The 174-foot-tall, 167,000 $ft.^2$ +student residence has a concrete foundation and incorporates two concrete elevator/stair cores. Large CLT panels supported by glulam columns comprise the bulk of the structure. The building's cladding is a wood-fiber high-pressure laminate.

Other tall wood buildings and wood buildings of all kinds constructed around the world in recent years include use a variety of composite lumber products and timbers in combination with CLT. Traditional wood construction has also benefitted from the extra strength and uniform design properties of structural wood composites.

It is highly likely that the future will bring many more large wood buildings to multi-housing and commercial and industrial structures around the world. The shift will result in greater reliance on renewable biomaterials, reduced energy intensity in production of building products, and improved environmental performance of the built environment.

Bioenergy

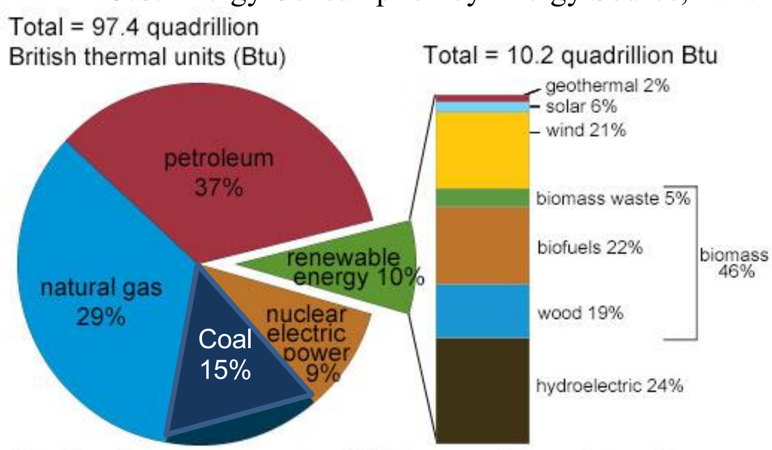
Bio-energy is not a new idea. The first deliberate use of bio-energy occurred when prehistoric peoples discovered how to use fire to keep warm. The use of fire for heating and later for cooking, pottery making, and to provide light goes back at least 200,000 years. Worldwide, the primary use of wood today is still as a fuel for heating and cooking.

As noted earlier, in the United States, wood was a principal fuel as recently as 1900. Thereafter, coal, oil, and natural gas became dominant fuels. However, the oil embargos of the 1970s (1973 and 1979) resulted in marked growth of wood consumption for fuel, with volumes consumed for that purpose briefly rising to near the levels of 1900 (Figure 1).

The oil shocks of the 1970s served to awaken many to the reality of U.S. vulnerability regarding petroleum supplies. Oil consumption within the U.S. declined for the first time in decades in conjunction with the first supply disruption, but then recovered quickly thereafter as supplies were restored. The second event led to more dramatic decline in domestic consumption, after which demand recovered much more slowly. These events resulted in interest on the part of the military and of the broader research community in development of alternative sources of energy, and particularly alternative sources of transportation fuels. The research agenda included energy crops and biofuels.

Subsequently researchers identified potential for annually producing over 1.3 billion dry tons of biomass in the U.S., a volume that could, by 2030, supply 5% of the nation's power, 20% of its transportation fuels, and 25% of its industrial chemicals and chemical feedstocks. This is roughly equivalent, in total, to 30% of 2010 U.S. petroleum consumption. The total includes energy potential from energy crops, agricultural crop residues, forest biomass from logging residues and thinnings, animal and other wastes, and algae. Biomass currently accounts for 4.6% of total U.S. energy consumption and 46% of renewable energy (Figure 7).

Figure 7
U.S. Energy Consumption by Energy Source, 2016



Note: Sum of components may not equal 100% because of rounding

Source: U.S. Energy Administration, Monthly Energy Review, Tables 1.3 and 10.1, April 2017. Preliminary data.

Transportation Fuels

The technical feasibility of liquid fuels production from biomass has long been established. Some reports indicate knowledge of ethanol production through fermentation as long as 9,000 years ago, although the motivation was likely drinking rather than fuel production.

Ethanol's first use in powering an engine was in 1826, and in 1876, an engine was built that would run on gasoline and ethanol. Twenty years later Henry Ford unveiled the Quadricycle, a vehicle designed to run on pure ethanol. The first Model T Ford (1908) was designed to run on ethanol, gasoline, or kerosene. Ethanol consumption in the U.S. rose to as much as 50-60 million gallons during World War I (1917-1918), then increased again several decades later in the course of World War II. In both cases, production was largely from corn. Ethanol also was used as a fuel in lamps, lanterns, and streetlights in the mid-1800s.

More recently, driven by investment and production credits, other incentives and mandates, subsidies, and an aggressive portfolio of research and development, production of first-generation (starch-based) ethanol in the U.S. has risen dramatically, increasing from about 2 billion gallons in 2003 to over 15 billion in 2016. Virtually all was produced from corn starch. Consumption of biodiesel, produced from soybeans, has also increased substantially in recent years; in this case the increase was from 0 in 2002 to over 2 billion gallons in 2016. Overall, biofuels accounted for 5% of U.S. transportation fuels in 2016.

Concurrent with growth of consumption of biofuels, research efforts have focused on technologies to enable use of lignocellulosic materials such as corn stalks or wood, rather than corn starch (corn kernals), as raw material for ethanol production – a development that will dramatically improve the energy balance of biomass-derived fuels. After decades of research, cellulosic fuels are now produced commercially, although still in small volumes (i.e. ~ 4 million gallons in 2016). Research has demonstrated that corn stalks, wood and other biomass can be converted to a range of liquid fuels ranging from bio-oil, to ethanol and biobutanol, to jet fuel, to gasoline. Syngas, also known as renewable natural gas, can also be produced. Biomass-derived jet fuel is today a reality, used by many of the nation's commercial airlines.

Generation of Electricity and Heat

The use of wood for generation of electricity and heat has also increased in recent years. Between 2010 and 2015, electricity generation from biomass in the U.S. grew 14%. In 2015, generation from biomass accounted for 11.3% of renewable electricity generation and 1.6% of total electricity generation. Nearly half of the electricity generated from biomass in 2015 was at industrial facilities outside of the electric power sector, such as pulp and paper mills. Within the electric power sector, biomass accounted for 6.3% of renewable electricity and 0.8% of total U.S. electricity generation.

Figure 8
Biomass Power Plant in Portsmouth, New Hampshire

Source: PSNH

The forms of biomass used in electricity generation include forest harvest residues (tops and branches), sawmill residues, and urban landscape trimmings. Many power plants that burn biomass are co-firing plants, wherein wood is used in conjunction with coal or natural gas. Some of these plants are combined heat and power operations, meaning that both heat and electricity are produced; in these operations heat, which would normally be wasted, is captured and used to provide hot water or steam for other uses. There are also opportunities to produce biochar which has multiple uses, including as a soil amendment or filtration element and can provide diverse environmental benefits.[1]

[1] For more information, see: *Biochar 101: An Introduction to an Ancient Product Offering Modern Opportunities*, Dovetail Partners, http://www.dovetailinc.org/report_pdfs/2016/dovetailbiochar0316.pdf

In addition to wood used for domestic electricity generation, about 6 million metric tons of compressed fuel pellets (mostly wood) were produced in the U.S. in 2016. Over 80% of these pellets were exported for use in electricity generation, primarily in the UK. Export volumes equate to about 0.07 quad of energy. The 18% of fuel pellets consumed domestically are largely used for home heating. Fuel pellets are reported to have been first produced in the western U.S. during the Great Depression (1930s) by a sawmill looking to market scraps from lumber manufacturing. The first use of wood pellets in wood stoves in the U.S. occurred in the 1980s as home heating from wood ramped up following the 1970s oil shocks.

Long-Term Outlook

The use of biomass to provide energy is controversial. Some fear deforestation and forest degradation from widespread reliance on wood as an energy source. Others point to monoculture cropping and devastating effects of intensive agriculture on water quality in primary biofuels production regions. Another concern is the use of agricultural land to produce fuel rather than food.

Because of concerns, many see the role of general use biomass fuels as transitory, with use limited to those purposes for which development of non-fossil alternatives would be challenging. A late 2016 Whitehouse report projected heavy future reliance on electric vehicles, with biomass seen as providing energy for transportation difficult to electrify, such as aviation and long-haul trucking. Heat production in certain industrial sectors was also envisioned. Even should transportation limitations as envisioned come to pass, the potential is nonetheless large, with annual fossil-based consumption of aviation fuel currently about 22 billion gallons, and diesel fuel at 61 billion gallons – of which 39 billion gallons is for long-distance travel.

Biochemicals

The recent estimate that biomass could provide 25% of industrial chemicals and chemical feedstocks is based on decades of research aimed at development of alternatives for fossil fuel-derived chemical feedstocks. These efforts have led to development of a number of thermochemical and biochemical conversion processes for converting biomass components to industrial chemicals, fuels, and power. Biochemical technologies use enzymes or microorganisms to convert biomass feedstocks to desired products (e.g., through fermentation). These kinds of technologies may be used alone, or may augment more traditional thermochemical technologies such as those used to remove wood extractives or separate fiber. Fermentation processes are most commonly used for the production of organic acids and ethanol. Thermochemical technologies may utilize catalysts (acid, metal, or a combination) and/or high pressure and temperature to convert biomass components to various products.

Through biochemical conversion technologies, products are derived from constituent sugars. Biomass sugars represent the most abundant renewable resource available. There are many ways to transform sugars into bioproducts. Many common products (citric acid, ethanol, lactic acid) are produced through fermentation. With a vast range of microorganisms and enzymes currently available and investigation ongoing, the fermentation of sugars holds great potential for new bioproducts. One of the most promising glucose derivatives is ß lactic acid for which there are many potential derivatives, some of which are new chemical products, and others that represent bio-based routes to chemicals currently produced from petroleum. Durable and biodegradable plastics are among the products that can be produced.

Other research has focused on isolation of naturally occurring nanocellulose and nanocrystals from biomass. Potential applications are many, and include use as formaldehyde-free binding agents, as a concrete additive to increase strength while reducing its environmental footprint, in production of flexible low environmental impact batteries and computer chips, in producing high viscosity films, and in applications ranging from medical, and pharmaceutical products, to cosmetics, hygiene, and absorbent products.

Economic Implications of Greater Reliance on Bio-Products

Several estimates have been made of the economic impact of the rising bioeconomy. An assessment of the 2013 U.S. bioeconomy indicated direct employment of 4 million, a value-added contribution to the overall economy of $369 billion, and a jobs multiplier of 2.64 – meaning that for every 1 biobased products job, 1.64 additional jobs were created in the United States.

A 2016 estimate contained in a Joint Federal Agency Report, published by the Biomass R&D Board, is a much more conservative estimate of the impact of the current domestic bioeconomy, indicating over a quarter million jobs and an economic contribution of approximately $50 billion. This estimate, however, excluded from consideration established forest and agricultural sector jobs (including those related to production, processing, and distribution of food, feed, and fiber), as well as the pharmaceutical sector. With these caveats, the report addressed potential growth of the domestic bioeconomy, estimating that by 2030, with efficient use of the roughly one billion ton annual biomass supply identified in earlier studies, total direct revenue could reach approximately $250 billion annually, with a total economic impact of $660 billion each year including indirect economic outputs. The report further indicated that the cumulative job benefit could amount to over a million new positions that cannot be outsourced from the United States.

As reported in 2016 by the Biotechnology Innovation Organization, McKinsey & Company expects that by 2020 biobased products will make up 11 percent of the $3.4 trillion (€3.130 billion) global chemical market. The company further indicated that sales of biobased products would reach $375 – $441 billion (€345 – €406 billion) by 2020, with a compound annual growth rate of 8 percent over the preceding decade. Worldwide growth of chemicals sales were projected at 4 percent annually. Company analysts indicated that biofuels and plant extracts would continue to comprise half of the projected sales of biobased products in 2020, but that the highest growth rates were expected in sales of new biopolymers and renewable chemicals, biocatalysts for industrial processes and biologic medicines, and biofuels. Another report indicated potential for producing two-thirds of the total volume of chemicals from bio-based material, representing over 50,000 products, and a $1 trillion annual global market.

In the area of bioplastics, European Bioplastics forecast in 2016 that global production capacity would rise from 1.7 million metric tons (mmt) in 2014 to 6.1 mmt in 2021. The organization further noted that about 60% of bioplastics production in 2014 was durable plastics, with an increase to 80% forecast for 2019. Markets for biodegradable plastics were also expected to increase substantially, from 0.7 to 1.2 mmt during the period 2014-2109.

Many more reports and forecasts have been issued. A common theme: glowing projections of rapid and sustained growth for the decades ahead. In other words, the potential is quite large.

An interesting question is how resurgence of the bioeconomy might impact various segments of society. One report suggests that the emerging bioeconomy has the potential to create unprecedented growth in the rural economy and create a higher level of self-sufficiency for farming and rural communities. Another indicates that the high cost of transporting biomass will necessitate decentralization of biorefineries across rural areas, and that local production of energy will simultaneously reduce the need to pay for the import of petroleum and the need to pay for the transportation of products to export destinations. The authors of this study conclude that, by becoming bioenergy producers, manufacturers and companies that are major consumers of processed energy will find rural areas more attractive than they do now.

The Bottom Line

There is considerable evidence that bio-based materials and products will become more common in the future, in the process causing a significant shift back toward an economy based on biological materials (i.e. toward a bio-based economy). Significant impacts are likely across major sectors of the economy, including energy, industrial chemicals, building materials, and related industries of all kinds. In the process, rural economies may benefit as raw material sourcing patterns change.

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