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Measuring the Bioeconomy: Economics and Policies

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Abstract

The emerging concept of bioeconomy offers several opportunities to address societal challenges. The bioeconomy is mainly driven by advances in microbiology, which can be applied to various processes that use biological resources by shifting consumer preferences and by yielding new insights into resource constraints related to such issues as climate and land. Although expectations are high, less is known about the economic importance of the bioeconomy. This article reviews the methodological challenges of measuring the bioeconomy, the approaches used, and the outcomes reported. The results show that measuring the bioeconomy is still in its infancy and faces a number of methodological challenges. Bioeconomy cuts across sectors and therefore cannot be treated as a traditional sector in economics. Economics must catch up with bioeconomy realities. For a comprehensive economic assessment, information about bioeconomy resources, compounds, and product flows is required. We outline innovations in data storage and analytical methods that would realize bioeconomy opportunities and help guide policy.

1. INTRODUCTION

The bioeconomy is high on the policy agenda worldwide. The US government published a National Bioeconomy Blueprint in 2012 (White House 2012), and its bioeconomy grew approximately 10% annually through the past decade (Carlson 2016). The European Union and several of its member states have approved bioeconomy research and policy strategies since 2010. The European Commission noted that the European bioeconomy has €2 trillion in annual turnover and employs approximately 9% of the EU workforce (2012, p. 17). Furthermore, each euro invested is expected to generate ten euros of added value across different sectors (Eur. Comm. 2012, p. 4). Equally, the major emerging economies of Brazil, India, China, and South Africa have integrated the bioeconomy in their key growth strategies, and a strong contribution to African development plans is expected (Virgin & Morris 2017).

Definitions of the bioeconomy differ but share many similarities, as shown in **Figure 1** (Germ. Bioecon. Counc. 2015a,b). The widely used definition by the European Commission is resource focused but includes the primary sectors as well as the up- and downstream sectors: "... it encompasses the production of renewable biological resources and their conversion into food, feed, bio-based products and bioenergy. This includes agriculture, forestry, fisheries, food, pulp and paper production, as well as parts of chemical, biotechnological and energy industries" (Eur. Comm. 2012, p. 9). Some other definitions explicitly consider public sector research and development (R&D) activities, whereas others relate mostly to the private sector (McCormick & Kautto 2013). Whereas bioindustry-focused definitions address the renewable energy and industrial sectors,

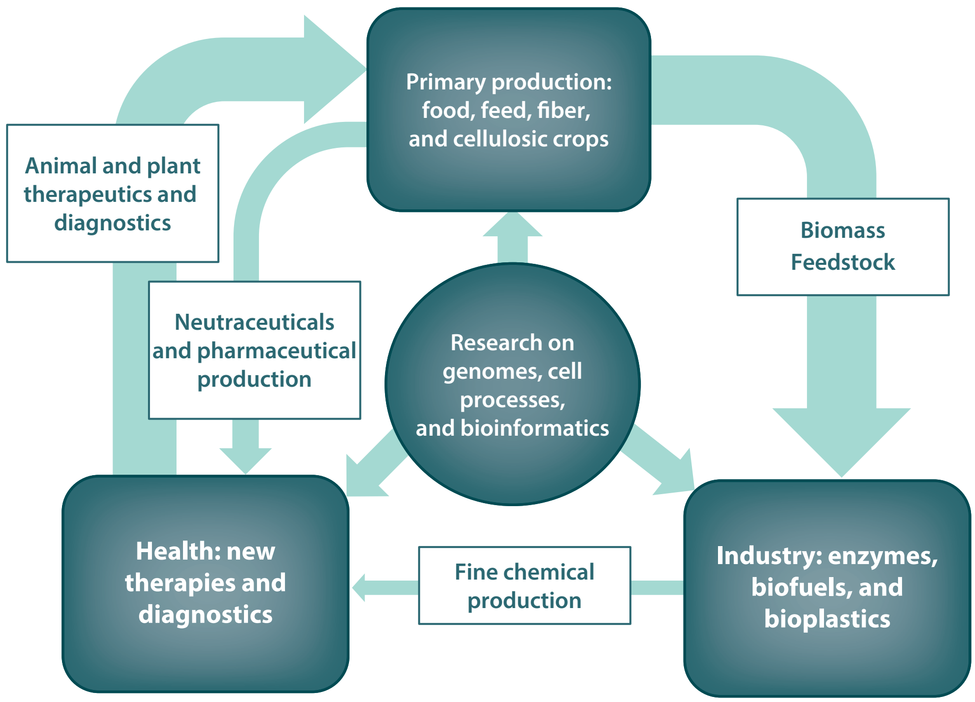

Figure 1

Current and expected integration across biotechnology applications. The size of the arrows indicates the relative importance in value. Figure adapted from the Organisation for Economic Co-operation and Development (OECD 2009).

resource-focused definitions have a strong agricultural perspective. Nutrition, health care, and converging technologies are part of more innovation-oriented bioeconomy definitions.

Bioeconomy is carried forward by societal and economic change, with a tendency toward sustainable development. Its basis is in innovations derived from research and comprises sustainable production and use of biological resources and processes and principles to provide products and services in all economic sectors (Swinnen & Riera 2013, Zilberman et al. 2013). Bioeconomy is cross sectoral and encompasses changing patterns in consumption as well (Wesseler 2015). According to the European Commission, the bioeconomy contributes significantly to a "circular economy," where "... the value of products and materials is maintained for as long as possible; waste and resource use are minimized, and resources are kept within the economy when a product has reached the end of its life, to be used again and again to create further value" (Eur. Comm., 2012 p. 2). But the bioeconomy concept is more comprehensive than the circular economy because it also aims for societal transformation and a biologization of industries and the economy with new products and solutions that facilitate a sustainable humanity (von Braun 2015). Bioeconomy also contributes to intelligent, sustainable, and inclusive growth that allows transition toward a "green economy" (OECD 2011a,b; 2016), a broader but less clearly delineated concept than bioeconomy.

Hence, measuring the bioeconomy has to be seen within the context of the broader issue of economic progress that considers issues of externalities and sustainable development. The impact measurement of investment in bioeconomy research and innovation, which cut across sectors, needs a framework. This is important for several reasons. First, without an appropriate measurement of the bioeconomy, assessing the impact of supporting policies and to what extent they have achieved their objectives will be difficult. Second, the bioeconomy, once defined, can be measured in different ways. Knowing the differences is important for the interpretation of results. Third, measuring the bioeconomy is not just about showing if the bioeconomy is big or small but rather how the bioeconomy developed and what its underlying driving forces are. Measurement should not only inform the ongoing evolution of the bioeconomy across different sectors, but it should ultimately be about economic and well-being–related outcomes.

This review is structured as follows. Section 2 discusses the broader theoretical issues related to measuring the bioeconomy and the implications for having a consistent framework. The third section provides an overview about the rise of the bioeconomy and the underlying driving forces. Section 4 surveys policy strategies around the world. The fifth section presents the different approaches used in measuring the bioeconomy, the results, advantages and disadvantages, and how they relate to a consistent framework. Section 6 discusses the results and implications for future research on the bioeconomy.

2. THEORETICAL ASPECTS OF EXTERNALITIES AND REGULATIONS

Developing the bioeconomy promises great opportunities for improving well-being and sustainable development (Eur. Comm. 2012, OECD 2009, Zilberman 2013). Bioeconomy strategies attempt to tap these opportunities by strategic science policy, incentives for private sector innovation, and inclusion of consumer and environmental stakeholders that may benefit from products and public goods resulting from bioeconomy innovations. Special attention, however, requires identification of externalities and appropriate regulatory regimes and consideration of opportunities under uncertainty and irreversibility because they determine expected social costs and benefits of a transformative bioeconomy. These issues are relevant for the measurement of bioeconomy, and therefore a brief theoretical review on them is provided here.

Sugden (2003) points out that the full value of individual opportunities is almost impossible to measure. But it is possible to measure whether sets of opportunities have changed over time and to identify influencing factors, in particular, the role of government policies. Opportunities are created by, for example, providing an environment in which people can translate innovation into new products (the supply side) that provide new opportunities for consumers (the demand side) (Du et al. 2016). If opportunities have increased over time, this should have a positive effect on individual freedom and well-being and translate into sustainable development, whereas the opposite effects should be observed if opportunities have been reduced (Arrow et al. 2012).

Government intervention can enhance or reduce opportunities. Environmental, food, and health safety regulations also serve a specific purpose: They are expected to improve well-being and may even provide new opportunities. Yet environmental, food, and health safety regulations may also reduce opportunities if they limit the availability of innovative and potentially beneficial products and services. Assuming that opportunities indeed matter, they also limit current and future individual well-being (Arrow et al. 2012). Such classic trade-offs between current and future benefits and costs may challenge the design and governance of innovative bioeconomy strategies (McCormick & Kautto 2013).

Trade-offs related to bioeconomy promotion may also result between competing uses of biomass and food security (von Braun 2015). Although these trade-offs are to be watched, they can be addressed by innovation and development of new types of biomass-based production and new techniques, as well by raising resource efficiency and new opportunities in biochemical processes with plants and microorganisms (Rosegrant et al. 2013). To the extent that bioeconomy entails new technologies, industrial processes, or change in natural resource use, concerns about impacts on human and animal health and on the environment come into play (see, for example, Eur. Counc. Environ. 1999). Rules and regulations have been implemented in response to these concerns (Smart et al. 2017). The implementation of rules and regulations entails administrative costs, and if compliance causes delays, that creates opportunity costs (Wesseler 2009, Wesseler & Zilberman 2014). Both kinds of costs have to be justified by the regulatory benefits, but uncertainties surround both of these costs and benefits (Arrow et al. 1996). Firms have an incentive to introduce a new technology and products derived from it if there is a market in its broadest sense. A potential market exists if the new product is superior in quality or price or if it adds to what is currently available (e.g., Krugman 1979, Lu et al. 2016). If consumers desire the new product or expect it will be superior, they adopt the innovation for the opportunity to increase their utility. Society may also benefit as more goods can be produced with the same amount of resources, or when the same amount of goods can be produced with fewer resources (e.g., Barrows et al. 2014 for the case of genetically modified crops).

The possibility of producing and consuming new products may have positive or negative impacts on human health and/or the environment. Some of those might even be irreversible (Wesseler et al. 2007). In the case that users exclude negative impacts from their net-benefit assessment, a restriction or ban to reduce negative impacts may be warranted (Wesseler & Smart 2014). However, if the impacts are included in the assessment and there are positive net gains, additional constraints may be unjustified from a social cost-benefit perspective. Furthermore, the impact of a new technology on human health and/or the environment may be smaller than the impact of the technology it replaces. This calls for measuring the changes in capital assets using shadow prices, as in the approach of Arrow et al. (2012).

Internalizing externalities by implementing a Pigouvian tax is one of the policy instruments widely discussed in the environmental economics literature. Although production of goods may cause external environmental or other kinds of damage, reducing their production to zero is in many cases suboptimal. Simple regulation of environmental externalities has been criticized, most prominently by Ronald Coase (1960). He argued that observing externalities does not necessarily justify government intervention, for example, via a Pigouvian tax. Stakeholders should have an incentive to internalize externalities. Coase suggests comparing the outcome of alternative institutional arrangements, including government intervention, but not only with the existing situation (Coase 2006). An intervention is warranted if a different institutional arrangement improves the outcome.

Coase's view was challenged by libertarians; for them, the question of government intervention depends on property rights. They argued that the courts should settle the problem of externalities.

> We have concluded that everyone should be able to do what he likes, except if he commits an overt act of aggression against the person and property of another. Only this act should be illegal, and it should be prosecutable only in the courts under tort law, with the victim or his heirs and assigns pressing the case against the legal aggressor. (Rothbard 1982, pp. 98–99.)

Yet implementing ex-post liability has its own problems due to liability avoidance, differences in wealth, and more (Shleifer 2010). Ex-post liability costs provide incentives for implementing ex-ante measures to reduce ex-post liability (Beckmann et al. 2010, Kolstad et al. 1990). In conclusion, externalities create additional costs under the Pigouvian, Coasian, and libertarian views; views on measuring costs and appropriate responses differ. However, these views reach the same conclusion: The mere existence or potential existence of externalities per se does not justify intervention.

The aforementioned discussion fails to differentiate explicitly between different types of external costs (Stiglitz et al. 2009). One concern about environmental and health impacts is that they may be irreversible and/or catastrophic; this is one reason that the precautionary principle has been mentioned in many regulations of bioeconomy technologies, most prominently in the Rio Declaration on Environment and Development under Principle 15 (United Nations 1992).

There are diverse interpretations of the precautionary principle. The most widely held example is that, for a new technology, the prospect of harmful effects takes precedence over the prospect of beneficial effects, but this line of reasoning results in logical inconsistencies (van den Belt 2003). A logically consistent method of addressing potential environmental impacts in line with the precautionary principle, and in particular, considering uncertainties and irreversible damages, is to perform an extended cost-benefit analysis. Wesseler et al. (2007), among others, suggested this approach, with additional net benefits needed to compensate for costs calculated using real-option models. An advantage of using real-option models is that they allow us to measure the value of future opportunities. In the most basic setting, future opportunities can be interpreted as options, where the owner of the option has the right but not the obligation to exercise the option, similar to a call option in financial markets (Dixit & Pindyck 1994). Real-option theory tells us that, although the investment opportunity yields a positive net present value, delaying the investment might be the optimal choice because losses can be avoided. Arrow & Fisher (1974) and Henry (1974) pointed this out in seminal papers in the early 1970s (Wesseler 2014b). The methodology has been applied to assess a wide range of issues, including the evaluation of firm investment in different sectors and in patents; the assessment of irreversibility effects; and the effect of subsidies and taxes on optimal investment decisions and on foreign direct investments. Model applications not only include irreversible costs but also irreversible benefits, optimal abandonment, entry and exit, and uncertainty over several variables, such as reversible and irreversible costs and benefits, discount rates, and others (e.g., Leitzel & Weisman 1999, Merton 1998, Mezey & Conrad 2010, Perrings & Brock 2009, Pindyck 2000, Smit & Trigeorgis 2004, Trigeorgis 1996).

So far, measuring future opportunities and their contribution to well-being and sustainable development has received little attention in the economics literature. Although there have been many attempts to measure sustainability, none have thus far established themselves. Examples of these attempts include the Ecological Footprint (Wackernagel & Rees 1996), the United Nations' Human Development Index (Sagar & Najam 1998), and Bhutan's Gross National Happiness Index (Mukherji & Sengupta 2004). Much discussed are the World Bank's measure of genuine savings and the approach of Arrow, Dasgupta, and Mäler on inclusive wealth and genuine investment (Arrow et al. 2012). Both concepts serve as measures of sustainable economic development over time. To compute the genuine savings rate, resource depletion and environmental degradation are subtracted from traditional net savings, while investment in human capital is added (Hamilton 2000, Hamilton & Clemens 1998). The concept of inclusive wealth and genuine investment is similar: A society's inclusive wealth is determined by measuring the shadow value of the economy's stock of capital assets (including manufactured capital assets, natural capital assets, and human capital). Genuine investment is then defined as a measure of changes in the economy's set of capital assets weighted at shadow prices. Accordingly, positive genuine investment is used as an indicator of sustainable development; in contrast to other approaches, this has a forward-looking perspective. Nonetheless, the approach does not consider opportunities, as the focus is on specific investments. Furthermore, future opportunities are inherently uncertain, and this uncertainty needs to be considered, in particular when opportunities involve sunk costs or other kinds of irreversible costs and/or benefits, as discussed above.

Although several authors argue that regulations can have negative effects on investments and reduce economic growth, others point out the positive effects of avoiding future damages. Porter has argued that environmental regulations may even have positive effects on firm-level growth (Ambec et al. 2014). It is important to note that regulations can have an effect on the allocation of research budgets of public and private sector research. If true, the reallocation of research budgets will have an impact on research, research results, and ultimately, on sustainable development. The effect of regulation and particularly environmental regulation on firm investment has been investigated (Ambec et al. 2014), but less is known about the effect of regulation on R&D in the public and private sector, or about the indirect effect on sustainable development via its effect on research. These issues need to be considered when evaluating the development of the bioeconomy.

3. BIOECONOMY: BEYOND THE AGRICULTURAL SECTOR

3.1. Advances in Biological Sciences

The bioeconomy is as old as human kind. Fermentation of grains provided the incentives to settle and cultivate crops (Katz & Voigt 1986). The fermentation of food products can be found worldwide, whether it is the fermentation of fish by the Inuit, the fermentation of milk into cheeses, yogurts, and similar products, or the fermentation of grain and fruits into beer and wine (Zilberman et al. 2013). The underlying biological processes have been refined over the past thousands of years. Biological resources have not only been used for food, they have also been used for fuel (bioenergy), feed, and fiber from the onset. There have long been debates and policies regulating the different uses of these resources. For example, the Code of Hammurabi (ca. 1754 BC) included regulations on land use (Johns 1903). The use of common pool resources, the Allmende, is a well-known institution in agricultural, environmental, and natural resource economics to regulate the conflict between pastoralists and agriculturalists over land use (van den Brink et al. 1995). Biological resources such as firewood have been used for heating since ancient times, and today it is the largest source of primary energy in Africa (Int. Energy Agency 2014). The regulation of food use has a long tradition, as the history of beer and chocolate shows (Squicciarini & Swinnen 2016, Swinnen 2011). This all is not surprising, considering that the bioeconomy has contributed to the rise and fall of societies (Diamond 2005).

Economic growth rates until the end of the seventeenth century in Europe and many other regions were relatively low. Growth in Europe started with the rise of capitalism (Harari 2014) and the expansion of European populations to the Americas (Crosby 1986), where they met favorable environmental conditions for producing food. Technical change in Europe further contributed to increases in productivity in agriculture, as demonstrated by the development of fertilizer use, and in particular, the development of the nitrogen fixation process to produce ammonia by the Haber-Bosch process, the rediscovery of Mendel's work applied to plant breeding, and the development of synthetic pesticides. This was later followed by mechanization, which further increased productivity and also provided labor for the rapidly growing industrial sector after the Second World War in Western Europe and the United States (Achilles 1993).

The development of recombinant DNA technology in the early 1970s was the start of modern biotechnology (Tramper & Zhu 2011). The Bayh-Dole act of 1980 in the United States, which provided universities and other forms of public and private organizations with the right to exploit patents that had been obtained with public funding, is seen as key for innovations in modern biotechnology (Stevens 2004). Some of the first successful products using rDNA technology were a vaccine for swine diarrhea in 1982 by the Dutch company Intervet Inc. and the production of human insulin for diabetics from genetically engineered (GE) bacteria by the US pharmaceutical firm Eli Lilly and Company. Since 1984, the Dutch company Gist-Borcades (now called DSM) started to insert the bovine chymosin gene in yeast cells, which allows for cultivating the yeast in large fermenters to be used for cheese production. In the late 1980s, the technology was adopted by cheese producers in Switzerland, followed by producers in the Netherlands, Germany, and France, in 1992, 1997, and 1998, respectively. Parallel to these developments, applications for enzymes produced from GE bacteria for bakery products have been introduced (Tramper & Zhu 2011). Today, a wide array of applications is available, including those in the food and feed sector, biofuels, biomaterials, chemicals, pharmaceutical, and biorefineries, among others (see Section 5).

3.2. Increase in Horizontal and Vertical Integration

In addition to far-reaching technological change, supply chains have become increasingly vertically and horizontally integrated (Wesseler 2014a). Looking at the agricultural sector only and not considering the increase in up- and downstream linkages with other sectors through different forms of contractual arrangements may create biases in policy analysis. Contractual arrangements cause hysteresis, resulting in delayed responses to changes in external factors such as market prices. For instance, farmers may sign up for an environmental service scheme but may not easily change their mode of production. Horizontal integration through mergers and acquisitions in up- and downstream sectors or voluntary collaboration at the farm level can change the market power of agents with economic and distributional effects along the value chain (Beckmann 2000).

Vertical integration can be seen as a supply-side response to differentiate products and to reduce the potential decrease in producer rents that might result from increase in product supply (Swinnen et al. 2015). Over the past two decades, we have witnessed substantial changes in agriculture food supply chains. For instance, a rapid rise in aquaculture production in Southeast Asia has paralleled vertical integration along the food supply chain (Belton et al. 2015). Similar developments in the fresh vegetable sector were supported by the increase in supermarkets (Reardon & Timmer 2014). These developments gained from improvements in the biobased sciences due to biodegradable packaging material as well as tracking and tracing technologies that provided opportunities for market differentiation (Reardon et al. 2015). Furthermore, new bioeconomy value chains emerged based on the increasing use of natural and renewable resources (Keegan et al. 2013).

3.3. Increase in Inter- and Intraindustry Trade

A further important aspect is the increase in inter- and intraindustry trade. The volume of global merchandise exports has more than tripled since 1990 (WTO 2014). The share of intraindustry trade more than doubled since the early 1960s (OECD 2010). Since 1960, agricultural production has tripled, while the agricultural trade volume has increased by a factor of six worldwide (FAO 2013). This increase in trade has increased interlinkages between international trade and agricultural and food production. A drought in Brazil, resulting in decreased soybean yields, has an effect on European animal farming, which happened in 2007–2008 (Backus et al. 2009). The international diversification in production will also be important for the future of food production and can substantially benefit from the bioeconomy (Rosegrant et al. 2013, Wesseler et al. 2017).

3.4. Shifts in Demand and Consumer Preferences, Partly Responded to by Policy

Bioeconomy is driven by both supply-side and demand-side impacts. Preference for biobased products is growing among global middle classes, not just in rich countries, including foods, wood-based construction materials, and textiles. McCormick & Kautto (2013) investigate this shift as it relates to risk considerations and lifestyle perspectives. Related externalities may far exceed classical externalities of preferences, such as excessive animal product consumption and adverse attitudes of genetically modified crops in many rich countries. Factoring in the footprints of greenhouse gases (GHG) and land use to product characteristics and their implicit labeling is an attempt to respond to such shifts in demand (Carrus 2017). Promotion of biobased and biopreferred products and related tax policies, as well as regulations such as the US policy giving biobased products preferences in public procurement (**http://www.gsa.gov/portal/content/105368**), are also an indication of such shifts in demand. The retail industry is also responding to such shifts in demand. The German government issued its National Program for Sustainable Consumption (Fed. Minist. Envir. Nat. Conserv. Nucl. Saf. 2016) with a range of policy actions that also relate to bioeconomy.

3.5. Advances in Information and Communication Technology

A further important development has been the wide and increasing application of information and communication technologies (ICTs). Internet and phone connections are now available almost everywhere, and news about major events spreads rapidly around the world. The speed at which information (news) is communicated (formally and informally) and its reach are positively affected by advances in the ICT sector, especially through mobile telephony and television networks and the Internet (including its social media platforms).

The biosciences, and especially genome sequencing and analyses, produce significant amounts of data. Data storage and information analysis tools are vital enablers for bioeconomy innovations, such as phenotyping, smart breeding, medical diagnostics, genome discovery and exploration, and therapy development. Agriculture, forestry, and fishery management are also advanced by ICTs. Precision agriculture, for example, uses satellite data and other environmental observations to optimize fieldwork, animal husbandry, and aquaculture (OECD 2016). Nano-, bio-, information, and cognitive technologies are converging and expected to enable further breakthroughs in the life sciences (Zanuy et al. 2006). For example, in the United States, a new consortium of nine US Department of Energy national laboratories was formed in October 2016 under the name of Agile BioFoundry. The consortium will be "working to standardize and streamline the entire biomanufacturing pipeline by uniting computer-assisted biological pathway design, process integration, process scale-up, and machine learning" (Bioenergy Tech. Off. 2016; **https://www.energy.gov/eere/bioenergy/articles/beto-establishes-consortium-national-laboratories-streamline**). As ICTs improve, many technologies become more affordable, and their use spreads globally, especially in developing countries. Their impacts on the bioeconomy, and therefore on society, will gain in importance (OECD 2016).

3.6. Increase in Globalization

A sixth important aspect that is closely related is the increase in globalization. According to the Levin Institute (**http://www.globalization101.org/what-is-globalization/**), this is understood

> . . . as a process of interaction and integration among the people, companies, and governments of different nations, a process driven by international trade and investment and aided by information technology. This process has effects on the environment, on culture, on political systems, on economic development and prosperity, and on human physical well-being in societies around the world.

Globalization goes beyond the increase in international trade and vertical and horizontal integration. We now find food chains such as McDonald's or Burger King and food processors such as Nestle or Unilever in almost every country; food retailers such as Walmart or the Schwarz Group are following closely behind. These developments are not undisputed (Greenpeace 2008, Winston 2002). The pervasive forces of digitization and globalization of the socioeconomic system change the framework condition of bioeconomy. They also foster complex positive externalities, which pose a challenge for measuring the bioeconomy.

3.7. An Increase in the Importance of Climate Change and Pressures on Land Use

Knowledge about the causes and implications of climate change has substantially increased over the past three decades. The bioeconomy offers opportunities to address adaptation to climate change and mitigation of GHG emissions (Zilberman et al. 2013). The use of new breeding technologies provides tools to develop crops that are suitable for a wide range of micro-agroclimatic conditions much faster and thereby can respond to climate change more effectively. Biobased industrial products typically have much smaller carbon dioxide (CO_2) footprints than comparable fossil-based products. However, they may have bigger water, eutrophication, and land-use footprints (OECD 2009, 2016). Quantification in terms of reduction in GHG emissions remains a challenge (Carrus 2017), and policies supporting GHG emissions savings may provide perverse incentives (Cornwall 2017). The use of bioenergy generated from biological resources, such as wood, manure, food waste, and algae, allows recycling of GHGs for the generation of energy in the form of fuel and electricity without increasing emissions (de Carvalho Macedo et al. 2015). This can even have a positive effect on emissions; i.e., it may reduce emissions due to differences in timing between the sequestration and release of CO_2 (e.g., Tassone et al. 2004).

The new initiative tabled at the Paris climate change conference (COP21) to massively increase carbon sequestration by enhancing soil carbon through changed land-use practices is noteworthy and has become a major global bioeconomy factor. The per annum increase of 0.4% in soil carbon and related carbon financing, as already introduced with auction approaches in Australia, could change the equation of biomass supply in markets and have complex implications for short- and long-run food and feed supply (UNFCC 2016). To quote the European Commission (2012, p. 4):

> A strong bioeconomy will help Europe to live within its limits. The sustainable production and exploitation of biological resources will allow the production of more from less, including from waste, while limiting negative impacts on the environment and reducing the heavy dependency on fossil resources, mitigating climate change and moving Europe towards a postpetroleum society.

3.8. Bioeconomy Innovations for Transforming Cities

In the coming 30 years, urban development and related construction may require more resources than any time in human history (Dobbs et al. 2012). Innovative solutions are needed to enable cities to function in a sustainable way and to provide quality of life for their inhabitants (Joss 2015). The cities of today need to change toward biosensitivity. This goal puts the bioeconomy at the center of sustainable urban development strategies (El-Chichakli et al. 2016). The integration of biological principles into urban planning and city life has become a key element for the achievement of greener cities. Locally coordinated production, provision, use, and recycling systems ensure that megacities function on the basis of closed material and energy cycles. Emissions, waste, and losses can be reduced, and renewable resources, cropping techniques, and biotechnology are seen as playing a major role in closing the loops (James 2015).

Measuring the bioeconomy in the urban context, i.e., valuing the societal contributions of a transformation toward biosensitive cities, is particularly challenging. In addition to resource substitution effects and their costs and benefits, far-reaching health benefits and externalities related to amenities (greening) should also be considered. Approaches for nonprice economic valuation have long been on hand in economics, but these approaches need appropriate adaptation to these multifaceted contexts to avoid either exaggerating or underestimating the actual and potential urban contributions of these bioeconomy innovations.

In an international Delphi study to explore flagship projects for the international bioeconomy, Bioprincipled City was rated as one of the most relevant examples (Germ. Bioecon. Counc. 2015a). Most participants estimated that the vision could be realized by 2040. Three cluster areas emerged: urban planning, architecture/buildings, and urban production.

- In the field of urban planning, the aspect of developing a sustainable city metabolism is to be considered. It relates to closing material and nutrient loops in cities, for example, by rainwater collection, cascading use of drinking water, wastewater purification, and nutrient recovery (e.g., recovering phosphorus from sewage sludge). Innovative ways of greening urban spaces are another relevant aspect of urban planning. Greening helps clean the air and balance temperature extremes in cities. Forested high-rise buildings (vertical forest) are examples; not meant as decorative attachment, they rather represent a part of an architectural concept, including an irrigation system. Self-maintaining greening systems coping with air pollution are what their inventors call "City Trees," a high-tech element cladded with a special species of moss, which absorbs poor air (Herberg 2016), and which planned to be tested in Hong Kong (Trentmann 2016).
- In the field of architecture and buildings, bioinspired design solutions are one aspect of a future bioprincipled city. Existing projects in this field can be seen, for example, in Hamburg, Germany, where the world's first building was equipped with an algae facade made of glassy bioreactors. This facade not only produces heat and biomass, it also binds CO_2 through the photosynthesis of growing green algae. According to model calculations, the facade could convert approximately 48% of the incoming sunlight into usable bioenergy. Moreover, the chlorella algae serve as light protection as they adjust their color to the sun's intensity. Every reactor is fixed with two glass plates, which further ensure thermal

insulation and noise protection (Gabrielczyk 2013). Biobased and residual materials can have improved material properties. In the Netherlands, facades and building elements are three-dimensionally printed with biobased plastic materials. These elements can be recycled or remodeled if needed. Innovative wood construction, for example, is used for high-rise buildings in Vienna, Austria, where the world's highest wooden building, the HoHo Building, was constructed. Recently, natural insulation materials have also enjoyed greater demand. Their production requires less energy, and they have positive effects on household climate and human health. Examples of raw materials used for insulation include wood fiber insulation materials, cellulose from defibrated old paper, hemp, wax, meadow grass, straw, and sheep's wool.

- In the area of urban production, aspects of green industrial production and urban farming are considered. Visions for green industrial production are developed, for example, by the Belgian architect Vincent Callebaut, whose Hyperion project aims to combine agroecology and sustainable food systems that grow up around six timber towers in New Delhi, India (Smith 2016). The project is further designed to integrate urban renaturation, small-scale farming, environmental protection, and biodiversity. The vertical village provides spaces for business incubators, living labs, coworking spaces, and multipurpose rooms. All apartments are equipped with cascading hydroponic balconies, and indoor furniture is made from natural materials, such as tamarind and sandalwood. Organic aquaponics and hydroponic greenhouses further provide all residents with fresh vegetables. Food is also produced in neighboring agroforestry fields, which ensure food autonomy for the residents (Smith 2016). Vertical farms and urban farming, however, are regarded with skepticism by many in terms of limitations of scale and productivity (Germ. Bioecon. Counc. 2015a).

4. NATIONAL AND REGIONAL BIOECONOMY STRATEGIES

The rise of the bioeconomy has resulted in policy strategies, which are partly endogenous to natural resource endowments, science capacities, and preferences. More than 45 countries pursue development of the bioeconomy in their policy strategies. Worldwide, nine countries and regions (including the European Union) have developed dedicated bioeconomy policy strategies (**Table 1**). These strategies typically represent a more holistic approach to promoting the development of the bioeconomy. They concentrate on leveraging the full potential of biological resources and processes across all economic sectors. Policy interventions span R&D support to demand-side measures. Such dedicated bioeconomy strategies have been developed for Finland, Germany, Japan, Malaysia, South Africa, Spain, United States, and the West Nordic Countries. The European Union as a supranational organization has released a proper bioeconomy strategy in 2012. The bioeconomy policy landscape remains rather diverse. Bioeconomy development is pursued in the context of research and innovation strategies, green or blue economy strategies, as well as industry strategies and high-tech (biotechnology) strategies (Germ. Bioecon. Counc. 2015a,b). Furthermore, many regional initiatives have emerged. For example, in Canada, very different bioeconomy strategies have been adopted in the provinces of British Columbia, Alberta, and Ontario (Birch 2016).

Across most countries, the development of bioeconomy policy strategies is motivated by meeting the grand societal challenges of the twenty-first century, such as climate change mitigation, global food security, and sustainable resources management. However, the bioeconomy is clearly understood as a means for green growth.

The objectives underlying the promotion of bioeconomy development are related to a country's or region's resource endowment, economic specialization, and state of development. For

Table 1 Dedicated bioeconomy strategies around the world.[a] Data from the German Bioeconomy Council (2015b)

Country/region	Strategy paper(s)	Priority areas of the strategy	Economic expectations
European Union	"Innovating for Sustainable Growth: A Bioeconomy for Europe" (Eur. Comm. 2012)	Food, agriculture, forestry, marine resources	Economic growth, reducing fossil fuel dependence, sustainable reindustrialization, competitiveness
Finland	"The Finnish Bioeconomy Strategy" (Finn. Minist. Envir. 2014)	Forestry, wood processing sector, health care	Economic growth, job creation, competitiveness, wealth creation
Germany	"National Policy Strategy Bioeconomy" (Fed. Minist. Food Agric. 2014) "National Research Strategy Bioeconomy 2030" (Fed. Minist. Educ. Res. 2011)	Agriculture, health and nutrition, industrial use of renewable resources, sustainable bioenergy	Competitiveness, renewable raw materials and energy from biomass, economic growth
Japan	"Biomass Industrialization Strategy of 2012" (Jpn. Minist. Agric. For. Fish. 2012) "Biomass Strategy of 2009" (Jpn. Minist. Agric. For. Fish. 2012)	Bioenergy, agriculture, forestry	Economic growth, rural development
Malaysia	"National Biomass Strategy 2020" (AIM 2013) "Bioeconomy Transformation Program" (MOSTI 2015)	Agriculture, forestry, fisheries, bioenergy, chemicals	Economic growth, competitiveness
South Africa	"The Bio-Economy Strategy" (DST 2013)	Agriculture, chemicals, health care	Economic growth, job creation, competitiveness
Spain	"The Spanish Bioeconomy Strategy: Horizon 2030" (Gov. Spain 2016)	Food, agriculture, forestry and the timber by-product sector, industrial bioproducts, bioenergy	Economic growth, job creation, competitiveness, sustainable productive sectors, circular economy
United States	"Agricultural Act of 2014" (USDA 2014) "National Bioeconomy Blueprint" (White House 2012)	Health, agriculture, bioenergy, food	Competitive and sustainable economy, rural development
West Nordic Countries (Faroe Islands, Greenland, Iceland)	"Future Opportunities for Bioeconomy in the West Nordic Countries" (Smáradóttir et al. 2014)	Agriculture, fisheries, bioenergy, aquaculture	Economic growth, competitiveness

[a]National strategy studies available at **http://biooekonomierat.de/en/international0/**.

example, oil-importing countries with large biomass resources promote development of the bioeconomy to strive for higher independence and generate income from their biological resources. Industrializing countries with a significant share of rural population and primary industry jobs consider bioeconomy development as a means for promoting rural development and social inclusion. Industrialized countries with fewer biological resources and a smaller share of primary industry jobs focus more on the opportunities arising from advances in the biosciences and biobased technologies (El-Chichakli et al. 2016). Most strategy papers consider ecological and socioeconomic sustainability aspects of the bioeconomy; however, they hardly define concrete objectives and how these will be monitored and measured. Most documents argue that sustainability standards need to be developed and agreed to internationally (FAO 2016).

5. APPROACHES TO MEASURING THE BIOECONOMY

Measuring the bioeconomy is a challenge because of its externalities, cost of regulatory regimes, and uncertainties of opportunities, as theoretically elaborated in Section 2. Measurement is complex because bioeconomy evolves in a global change context of digitization, globalization, urbanization, science evolution, and changing preferences, which makes it partly endogenous to these forces (Section 3). Furthermore, bioeconomies evolve and are driven by diverse policy strategies (Section 4). In view of these challenges, it is obvious that there is not a one-size-fits-all approach for measuring the bioeconomy. Rather, it may be helpful for science, policy, and industries to combine measurement approaches and accompany them with a comprehensive narrative about economic opportunities, competitiveness, externalities, and sustainability gains.

Several approaches may be used for measuring the bioeconomy, but each needs to be scrutinized in regard to what is measured and how. One approach that has been used most widely is based on using the system of national accounts to provide an overview about the contribution to the regional or national economy and to employment and consumption shares. As mentioned above, this might not provide a detailed enough picture about future opportunities. Those can be provided by considering bioeconomy clusters, the emergence of key technologies, and bioeconomy innovations by evaluating patent applications and private and public sector investments. In addition, the bioeconomy's contributions to environmental sustainability and people's well-being would need to factor in health and ecology effects that may be covered in systematic narratives about bioeconomy measurement.

5.1. Changes in Value Added and Turnover

Measuring the contribution of the bioeconomy to economic growth requires knowledge about the share of the bioeconomy in the overall economy. As a database for identifying the development of the bioeconomy, the systems of national accounts have been used in many studies (**Table 2**). By identifying and summing the value-added contributions of the sectors and subsectors that are part of the bioeconomy, the share can be identified, and changes over time provide information about the growth of the bioeconomy. A problem is that the different sectors and subsectors composing the bioeconomy are not easily identifiable (Carlson 2016). There is common agreement that the agriculture, forestry, and fishery sectors belong to the bioeconomy. The inclusion of the paper and pulp industry and the food industry is also not questioned. Accounting approaches differ regarding inclusion of the chemical industry and pharmaceutical sector as part of the bioeconomy. The same applies to the automobile industry, where parts can be considered to belong to the bioeconomy, such as leather for car seats or insulation materials based on biofibers and other sectors of the economy (Fed. Minist. Educ. Res. 2015).

Heijman (2016) proposes a simple input–output model where the share of the bioeconomy in value added is defined based on the share of bioeconomy inputs. Carlson (2016) compiled a number of different information sources, including financial reports of companies, surveys, and consulting reports. Efken et al. (2012) measure the importance of the bioeconomy in Germany in terms of its contribution to the value-added production within the economy as a whole and to employment. The calculation is based on the survey about material and goods received (MGR) by companies (SBA 2009). The German Federal Statistical Office collects data every four years.

Table 2 Size of the bioeconomy in local currencies

Study	Region	Period	Measure	Methodology
Efken et al. (2012)	Germany	2007	Value added: €164,500 (7.6% of GDP)	Input–output model, excluding agriculture input sector (e.g., equipment, fertilizer, pesticides, machinery)
Carlson (2016)	United States	2012	Turnover: US$324 billion (>2% of GDP)	Compiling information from several sources (e.g., financial reports, surveys, consultancy reports)
Golden et al. (2015)	United States	2013	Value added: US$369,300 (2.2% of GDP)	Results based on the IMPLAN model; excludes the following sectors: energy, livestock, food, feed, and pharmaceuticals
Heijman (2016)	Netherlands	2008–2012	Value added: €32,578–38,828 (6.6–7.2% of GDP)	Input–output model in 2008; basic prices
Nowicki et al. (2008)	EU25[a]	2005	Turnover: €453,741	Value of biobased materials excluding food and feed derived from PRODCOM[b]
Ronzon et al. (2015)	EU28[c]	2013	Turnover: €2,036,621	Value of the bioeconomy derived from EUROSTAT in combination with sector shares of biobased products derived from studies by NOVA Institute
Rosegrant et al. (2013)	Global	2050	Contribution in percent to food production: +11% for meat; +10% for cereals; increase in GDP growth from 3.2% to 3.6%	IMPACT model: a partial equilibrium, multicommodity, multicountry model combined with general equilibrium model GTEM
Vandermeulen et al. (2011)	Flanders, Belgium	2010	Value added: €1,116 (1.8% of GDP)	Industry survey considering biobased energy and biobased products

[a]EU25 refers to the European Union member states between May, 2004 and December, 2006.
[b]PRODCOM, Production Communautaire; provides statistics on the production of manufactured goods for mining, quarrying, and manufacturing, representing sections B and C of the Statistical Classification of Economy Activity in the European Union (EUROSTAT; **http://ec.europa.eu/eurostat/web/prodcom**).
[c]EU28 refers to the European Union member states from July 2013 until present.
Abbreviations: EU, European Union; GDP, gross domestic product; GTEM, Global Trade and Environmental Model; IMPACT, International Model for Policy Analysis of Agricultural Commodities and Trade.

MGR is the sole official statistic about companies' input structures. The input structure is based on the classifications of MGR in industry that contain 584 categories of goods. Data collection is done by stratified random sampling based on the statistical business register of the German Federal Statistical Office, which serves as the population. This approach results in a more refined picture about the bioeconomy and linkages between different sectors. Similar approaches have been implemented for specific products (Nowicki et al. 2008, Ronzon et al. 2015). Rosegrant et al. (2013) link a detailed partial equilibrium model for the agricultural sector with a general equilibrium model to identify the contribution of the bioeconomy to forecasting food production as well as overall economic growth for the year 2050.

5.2. Bioeconomy Clusters

The development of the bioeconomy is also reinforced by policies through supporting clusters. Some clusters in the bioeconomy have emerged naturally around institutes of higher education, whereas others have been initiated by policy support but are also often linked with institutes of higher education. Clusters benefit from the high density of human capital in a specific field, often attracting additional capital for investment and reinforcing the strength of the cluster. A potential threat for clusters is the high level of specialization that increases the vulnerability to external shocks (Porter 2003). In the bioeconomy of the San Francisco Bay Area, Boston/Cambridge, Massachusetts, and the triangle of Brussels, Ghent, and Leuven are ranked by several sources as being the most important as measured by employment and number of companies. Those clusters can be considered to have formed naturally with less specific government support and investment. A number of other bioeconomy clusters have been formed or reinforced by specific public support; the Netherlands represents one such case (Langveld et al. 2016). The European Union maintains a website of country self-reported clusters. Data for the European Union and Japan show that the bioeconomy clusters dominate with 39% and 53%, respectively. In Europe, Spain (29), France (25), Romania (13), and Germany (10) report the highest number of bioeconomy related clusters. In the European Union and Japan, those clusters receive government support. For the United States, strong bioeconomy clusters have been identified in additional areas to the aforementioned examples: the metro areas of San Diego, Raleigh-Durham, New Jersey/New York City/Westchester, Los Angeles/Orange County, Philadelphia, suburban Maryland/Washington, DC, Minneapolis-St. Paul, and Seattle (JLL 2014). Extrapolating from science and start-up clusters to economic net benefits is a stretch and cannot just be focused on the local economy; it also needs to integrate important spillover effects.

5.3. Emerging Key Technologies

An issue closely related to economic growth and bioeconomy clusters is the development of emerging key technologies. Science innovations that initially had no relation to bioeconomy but may become significant game changers for it in the future were developed in the early 1970s at the University of California, San Francisco and Stanford University (Chem. Herit. Found. 2015). The CRISPR-Cas technology has mainly been developed at the University of California, Berkeley and the Massachusetts Institute of Technology (Egelie et al. 2016). Other new technologies can be linked with leading bioeconomy clusters (Schaart et al. 2016). The CRISPR-Cas technology promises great successes for human health and animal and plant breeding.

Other emerging key technologies are related to producing platform chemicals using biological resources, such as lignocellulosic materials. Lignocellulose is a resource of interest, as it is widely available and can be sourced from timber, by-products from wood processing, and cultivation of crops and green waste. One important platform chemical among other biobased acids is biobased succinic acid (Cok et al. 2014), with a market value of more than US$5 billion per year. The efficient conversion of lignocellulose into useful sugars depends on enzymes used in the bioreactors. Those enzymes are produced using genetic engineering methods. Here, the circle closes, where the development of biobased products does depend on microbiological technologies that are contested in some parts of the word and in Europe in particular. The new microbiology tools developed in the omics field have contributed to advances in industrial biomanufacturing. Biomanufacturing allows the establishment of small profitable units, as processes operate at much lower temperature levels than fossil-based chemical facilities (Clomburg et al. 2017).

The previous sections have illustrated the close link between research institutions, the development of key technologies for the success of bioeconomy, and the potential contribution to economic growth and measurement difficulties. Section 3 discussed the role of regulation. Missing from the discussion are the implications on innovation from a macro perspective.

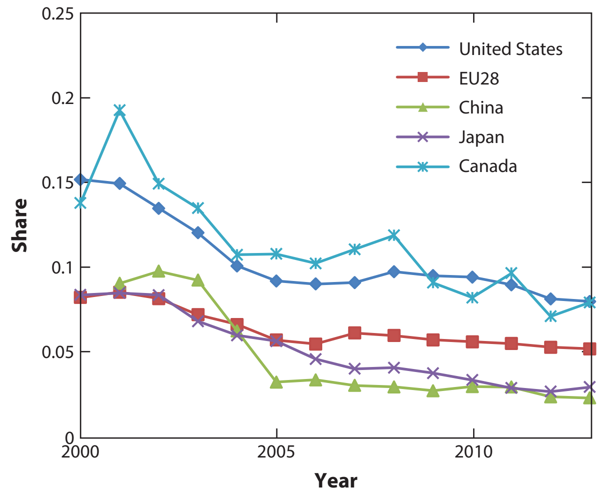

Figure 2

Share of the number of patents in the biotechnology sector from the number of patent applications filed under the international Patent Cooperation Treaty by priority year. Data compiled from the Organisation for Economic Co-operation and Development (OECD 2016). EU28 refers to the European Union member states from July 2013 until present.

5.4. Bioeconomy Innovation Activities

Bioeconomy product innovations are emerging quickly and have started to compete in the markets. A collection by the German Bioeconomy Council (2015a) lists 45 examples of consumer and manufacturing goods. Although the market shares of these goods remain small, one way of measuring them and the innovation contribution of bioeconomy is at the final product level.

The science and innovation development of the bioeconomy may also be assessed by looking into patent data. Patents are a measure of innovations by the public and private sectors. They also provide indications about the innovation in different fields as well as by different regions. **Figure 2** shows the share of patents in the field of biotechnology of total patent applications since 2000, as reported by the Organisation for Economic Co-operation and Development (OECD 2016). The share and number of patent applications show a continuous decline. This is in line with more detailed analyses of general patent data in biotechnology in the United States, which show an increase until approximately 2000, followed by a continuous decline. One exception is China, where the share of patents in the biotechnology sector has increased.

Figure 2 further shows that patent applications for biotechnology play a relatively more important role in Canada and the United States than in Europe, Japan, and China. The relative importance changes if the patent applications are valued by gross domestic product (GDP) in current prices or in purchasing power parity per capita, as illustrated in **Figure 3**. In that case, the relative importance of the biotechnology sector by country or region changes. The European Union and the United States are very close, but by this measure, the importance of the biotechnology sector in Canada declines in comparison to other countries and regions.

The overall decline in patents in the biotechnology sector in absolute as well as relative numbers is not surprising, as the major breakthroughs occurred in the late 1970s and early 1980s. Nonetheless, a more detailed look at some specific sectors show a somewhat different picture. Patent data for innovation in biofuels show that it peaked around 2011–2012 (Albers et al. 2016),

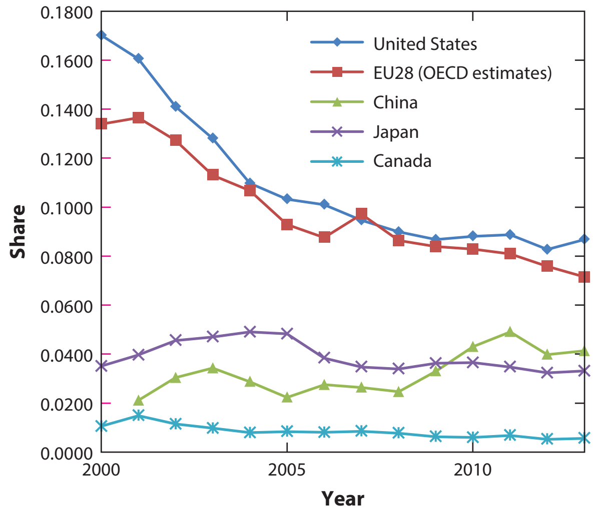

Figure 3

Share of the number of patents in the biotechnology sector under the international Patent Cooperation Treaty by priority year by gross domestic product per capita. Data compiled from the Organisation for Economic Co-operation and Development (OECD 2016). EU28 refers to the European Union member states from July 2013 until present.

and based on the number of patents granted, China has been by far the most active country, followed by the United States. A similar picture emerges for the filing of patents related to the emerging CRISPR-Cas technology, where the number continues to increase (Egelie et al. 2016).

Although the graphs in **Figure 2** and **Figure 3** provide information about research intensity in general, analysis by sector can reveal information on which sectors are more research intensive. **Table 3** lists private sector research expenditures for the different sectors of the bioeconomy as reported by the Bioeconomy Observatory of the European Union. The data clearly show that private sector R&D investments mainly consist of sectors manufacturing pharmaceuticals, medicinal chemicals, and botanical products, with approximately 45% of investments; this is followed by the sector manufacturing basic chemicals, with approximately 28%. Although caution is needed when directly using these numbers, the data show where the investment priorities are.

5. SUMMARY AND OUTLOOK

The rise of the bioeconomy affects many sectors of the economy. Several governments support the bioeconomy through direct and indirect investments. At this stage, the contributions to economic change are still uncertain, as many of the developments are still in their infancy. Recent developments in the biological sciences offer great potential not only for the more efficient use of biological resources for food, feed, fiber, fuel (energy), and industrial products (mainly via enzymes) but also for the development of the health sector. The more efficient use of biological resources also provides new opportunities to respond to the challenges posed by climate change. The generation of bioenergy, if carefully assessed for externalities via land-use change, can reduce GHG emissions. Efficiency gains in plant breeding allow us to better adapt to climate change at the local level. Adapted land use for soil carbon sequestration in conjunction with incentivized land-use change can become a significant component of the bioeconomy, but the opportunity costs as reflected in potentially lost outputs need attention.

Table 3 Private sector investments in the bioeconomy for selected European countries in millions of euros

	100% biobased transformation sectors[a]						Partly biobased sectors[a]					
Country[b]	**A**	**B1**	**B2**	**B3**	**B4**	**B5**	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
NL	172.26	388.51	2.38	1.95	8.77	0.67	10.96	554.09	349.74	95.58	87.14	100.75
FR	150.44	NA	NA	14.39	40.88	6.11	75.72	834.42	831.01	703.53	17.50	129.31
DE	138.30	NA	NA	19.80	58.10	6.70	64.40	3495.80	4062.00	956.00	39.90	70.60
ES	53.26	NA	NA	12.66	24.91	11.78	32.45	242.21	635.56	102.14	18.93	155.70
BE	25.84	121.65	0.07	5.67	10.42	7.69	43.62	350.22	1427.92	91.16	8.66	56.24
SE	22.26	NA	NA	NA	100.67	NA	NA	NA	858.49	23.48	9.52	17.28
UK	14.29	244.73	75.12	1.61	10.14	1.50	26.39	327.34	609.06	93.67	57.61	43.21
HU	14.26	15.49	0.63	0.90	2.05	NA	NA	11.66	193.11	7.70	1.48	3.66
DM	6.98	68.44	0.78	1.44	1.65	NA	1.53	235.58	821.02	48.94	6.12	5.29
FI	4.94	NA	NA	9.60	75.91	NA	NA	128.86	116.82	33.43	7.64	49.66
CZ	4.64	13.37	0.00	1.70	1.30	0.75	9.10	41.11	43.78	28.25	2.95	14.75
IT	3.30	150.30	NA	13.60	48.30	120.70	100.10	338.80	578.40	234.90	52.50	31.90
IR	2.11	NA	NA	8.09	NA	NA	NA	49.75	127.19	10.86	NA	2.55
EE	0.06	1.37	NA	NA	NA	NA	NA	1.54	3.19	0.90	0.23	0.35
LT	NA	0.10	NA	NA	NA	NA	1.92	0.20	4.94	NA	NA	NA
Total	612.93	1003.95	78.98	91.39	383.10	155.90	366.19	6611.59	10662.23	2430.51	310.18	681.23
%	2.62%	4.29%	0.34%	0.39%	1.64%	0.67%	1.57%	28.27%	45.59%	10.39%	1.33%	2.91%

[a]A, Biomass production sector; B1, food products and beverages; B2, tobacco products; B3, manufacture of wood and of products of wood and cork, except furniture; B4, manufacture of paper and paper products; B5, manufacture of leather and related products; C1, manufacture of textiles; C2, manufacture of basic chemicals; C3, manufacture of pharmaceuticals, medicinal chemicals, and botanical products; C4, manufacture of rubber and plastic products; C5, manufacture of furniture; C6, construction.

[b]BE, Belgium; CZ, Czech Republic; DE, Germany; DM, Denmark; EE, Estonia; ES, Spain; FI, Finland; FR, France; HU, Hungary; IR, Ireland; IT, Italy; LT, Lithuania; NL, the Netherlands; SE, Sweden; UK, United Kingdom.

Data compiled from the European Bioeconomy Observatory, National Bioeconomy Profiles. Data refer mainly to the years 2011 and 2012. The details are provided in the respective National Bioeconomy Profiles (**https://biobs.jrc.ec.europa.eu/country**). Abbreviation: NA, not applicable.

Measuring these effects at the national level requires detailed monitoring of the product flows, for instance, as part of input–output analyses. This will provide information about the size of the bioeconomy cutting across sectors, as well as its contribution to economic growth and related labor market effects. Related efforts have been initiated in EU member states, and other countries might follow their lead. The importance of monitoring the product flow is expected to increase in the near future. Certification schemes for biobased products are increasing. Companies use them for marketing their final products to create, improve, or maintain a green image in response to consumers' demands. This can have implications for international trade if standards between countries differ. A fruitful area for future research will be to investigate the development of those standards and potential international trade effects.[1]

The location of bioeconomy clusters and biorefineries is predominantly in rural areas and has the potential to stimulate additional economic growth there. This is particularly important for developing countries, where most of the population lives in rural areas and where the share of the

[1]Due to Engel's Law, the share of the agricultural and food sector declines with economic growth and may also result in declining terms of trade of the agricultural sector. Using biological resources not only for food and feed production but also for other uses has the potential to reduce or to even reverse this effect.

agricultural sector is still relatively high. The bioeconomy may provide opportunities to maintain employment opportunities in rural areas and strengthen the agricultural sector. More research should investigate opportunities for developing countries, which so far has mainly concentrated on the bioenergy sector. This would improve our understanding about more diverse opportunities.

Studies investigating innovations in the bioeconomy by using patent data provide some interesting results. The EU member states show a decline in patent applications for the different sectors of the bioeconomy in comparison with other regions of the world. The OECD (2009) has suggested that this is an effect of regulations facing the industry. If this is indeed correct—some studies provide support for this view (e.g., Graff et al. 2013, Smart et al. 2015)—what on the one hand is created with public sector investment in R&D is constrained on the other hand by public sector market intervention. This is an area where additional theoretical as well as empirical research is needed to better understand the interdependencies between innovation and regulation policies.

As the bioeconomy continues to emerge in policy agendas, the different approaches to measuring the bioeconomy should not be surprising. A first and quite traditional approach is to approximate the bioeconomy as a share of the GDP, pretending that the bioeconomy is actually a sector that can be identified by the flow of products and services. Related to this is the estimation of employment shares of the bioeconomy. A second approach is to measure the share of renewable biobased content embedded in the economy's products and services; this represents a physical bioeconomy measurement. A third approach is to consider the bioeconomy as being of a pervasive nature; it is not a sector, but is more like a digitalization. That would call for outcome measures rather than sectorial measurement or product (bio-) content measurement, as in the first two approaches. Outcomes would include reduced carbon emissions and sustainability of water, soil, and biodiversity improvements, each of which is measured in technical and economic ways, including nonprice measurement approaches. Well-being outcomes are also included, such as health improvements (e.g., reduced air pollution, people's actual health related to environmental factors), and improved amenities such as greener cities. The first approach, though a necessary step, is seen as unsatisfying because it simplifies the bioeconomy into a sector, neglects its externalities, contains all of the shortcomings of GDP accounting, and thus underestimates the bioeconomy's value to society. The second approach can only serve intermediate purposes, because such a "physiocratic" concept of bioeconomy is not meaningful, per se. Moreover, a higher biobased content in the economy's products and assets does not say much about sustainability, for example, about the resources' origins and how their production and utilization relate to sustainability. Only the third approach can satisfy economic theory and people's preferences, but obviously this is the most demanding approach.

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