Journal Pre-proof

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PII: S0160-791X(19)30502-0

DOI: https://doi.org/10.1016/j.techsoc.2020.101242

Reference: TIS 101242

To appear in: *Technology in Society*

Received Date: 4 October 2019

Revised Date: 1 February 2020

Accepted Date: 15 February 2020

Please cite this article as: Wydra S, Measuring innovation in the bioeconomy – Conceptual discussion and empirical experiences, *Technology in Society* (2020), doi: https://doi.org/10.1016/j.techsoc.2020.101242.

Measuring innovation in the bioeconomy – conceptual discussion and empirical experiences

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Measuring innovation in the bioeconomy – conceptual discussion and empirical experiences

Abstract

Innovations in the bioeconomy are expected to provide new solutions to major economic, societal and ecological challenges like resource depletion, food insecurity or climate change. However, information about innovation activities in the bioeconomy and its outcomes is scattered and more systematic measurement efforts are useful for policy making to assess its impact and whether objectives are met. This article provides an overview of information needs and data availability for innovation indicators. Furthermore, data for key input and throughput indicators are presented and discussed for the bioeconomy in Germany. The data indicates a rather strong role of Germany for publications and patents. However, the commercial success remains unclear, because of current limitations in information availability about the output and outcome of innovations efforts. Here, the most critical information gap in exist. In order to improve this situation additional data collection such as innovation survey for the bioeconomy would be needed.

Keywords:

Innovation indicators, bioeconomy, monitoring, patents, innovation

1. Introduction

The bioeconomy is expected to provide solutions to major economic, societal and ecological challenges like resource depletion, food insecurity or climate change. It is expected that new applications are developed and existing markets will be transformed. Hence, the bioeconomy may have significant impact on value added, employment, distribution of profits and sustainability. To achieve these goals, several developments such as appropriate political framework conditions or better addressment of societal concerns are needed. Moreover, significant progress in the production and use of biogenic resources needed and further innovation is necessary. Life and biological sciences and technologies are required to provide superior performance of bio-based processes, products and services, ensure their sustainability and to improve cost-competitiveness. Indeed, there is a high innovation potential in the bioeconomy ranging from the usage of mostly untapped feedstock (CO_2, waste, algae), optimized microorganisms, digitalization in farming, social innovations (urban gardening, collective agriculture, etc.) [1, 2]. Bio-based innovations are not only relevant in high-tech sectors, but also in traditional segments, such as the provision of new materials in textiles (e.g. spider silk) or developing new protein alternatives in the food sectors. Many strategies emphasize the need for new innovations to achieve the respective goals [3–5]. Various countries are pursuing large efforts to support R&D and innovation in the bioeconomy with significant advances. However, information about the progress of the bio-economy and in particular regarding activities and outcomes of these innovation activities is scattered.

In the last years, there have been significant efforts to measure the economic contributions of the bioeconomy [2, 3, 6–12]. These studies or articles have provided insights on the conceptualization of the measurement of the bioeconomy, current status of the bioeconomy, e.g. in terms of job, certain such as socio-economic accounting, estimations of the bio-based shares in sectors. Moreover, there are some attempts to assess the sustainability performance of the bioeconomy [13–15].

Those contributions provide very valuable insights regarding the development of the bioeconomy. However, they hardly provide a more dynamic and detailed view and there have been hardly attempts to measure the innovation process to the bioeconomy.

A proper and broader measurement of ongoing innovation activities and its outcomes is of high value. In order to get a sound basis for further political decisions, proper measurement, monitoring, and reporting the outcomes of efforts are needed [2, 3]. Such activities may enable to identify certain shortcoming throughout the innovation process, such as missing innovation activities or commercialization efforts. Moreover, the monitoring of its actual impact on the environment and the economy is important to know, whether the expectations to the bioeconomy strategies and funding programmes are realized. The Joint Research Centre (JRC) of the European Commission discussed some selected innovation indicators for the former Bioeconomy Observatory [16]. However, they focussed empirically on those sectors that can be counted entirely to the bioeconomy and did not cover emerging developments for bio-chemicals or bio-based plastics as the chemical or plastic sector are only partially bio-based. While consequent work of the JRC on economic indicators also covers the later ones [17], this hasn't been applied for innovation indicators.

The aim of this contribution is to improve the measurement of innovation in the bioeconomy, to discuss what kind of information may be needed to understand innovation patterns in the bioeconomy and to assess the current data availability. This perspective aims to complement the undoubted important economic and sustainability measurements of the bioeconomy referred above. Moreover, available empirical data for different innovation patterns – mainly input and throughput indicators – of the bioeconomy is presented and potential future needs for data collection are identified. For the empirical analysis we mainly focus on Germany because of the data access (e.g. for linking patents to companies) or data availability on more disaggregated levels (e.g. for education indicators). Moreover, Germany can be regarded as one of the front-runners in terms of initiating political strategies on a federal and regional level with the launch of a research as well as political strategy for the bioeconomy [14, 18–20] and the impact of innovation activities has become an issue of interest [12, 21]. We discuss the transferability to other regions or the European level in the results section.

The paper is structured as follows. First, we discuss key conceptualizing issues regarding the measurement of activities in the bioeconomy. Then we turn the focus to general concepts of innovation measurement and its suitability for the bioeconomy. In section 3 we discuss concrete the data present selected results for Germany. In section 4 we discuss open issues and ways forward to improve the innovation measurement for the bioeconomy.

2.Innovation measurement in the bioeconomy

2.1 Statistical delineation of the bioeconomy

A critical issue for many indicators of the bioeconomy is to define the bioeconomy and to set its boundaries concerning the sectors that are attributed to the bioeconomy [2]. The strategies of the various countries differ significantly in their definition and focus of activities [14, 19]. Currently, there is no generally accepted definition of the bioeconomy. According to a widely used definition by the German Bioeconomy council constitutes "the production and utilization of biological resources (including knowledge) to provide products, processes and services in all sectors within the framework of a sustainable economy” [22]. As such a definition is rather broad, in particular two important questions for monitorings arise.

The first question relates to the definition to biogenic resources. While the focus of many studies bases explicitly on biomass, a broader view may include processes in which biological resources such as living organisms (plants, animals, microorganisms) or parts thereof (e.g. DNA, enzymes, etc.) are used as process active ingredients. As the later mentioned resources are very important from an innovation perspective, we include them in our focus and hence have a broader view than concepts only relying on biomass [6, 15]. The second question concerns the sectoral boundaries of the bioeconomy. As Wesseler and Braun [2] state “A problem is that the different sectors and subscetors composing the bioeconomy are not easily identifiable.“ Many current attempts distinguish sectors.by their reliance on biogenic resources as inputs to production processes [6, 17, 23]. Varying to the concrete definition, the bioeconomy encompasses agricultural sector, food sector, pulp and paper, as well as those chemicals, plastics, textiles based on bio-based resources and many more. The majority of measurement approaches include the whole agricultural sector, as well as the whole user sectors of biomass, such as food as well as pulp and paper, when calculating economic figures [17, 23].

From a methodological point of view, a main challenge for many indicators is that important sectors for the bioeconomy, such as chemicals, textiles, rubbers and plastics are not 100% bio-based economic sectors, including the oil-based products or waste-based processes. Hence, information for sectors from national accounts cannot be used directly as they would overestimate figures for the bioeconomy. Instead, there have been some attempts to measure their reliance on biogenic resources as inputs to production processes. Consequently, bio-based shares for sectors are estimated and used as a proxy to estimate the proportion of the bioeconomy in a certain sector [8, 17, 17, 23].

From a conceptual point of view, there is significant criticism by stakeholders that those statistical boundaries overstate the importance of traditional segments of the bioeconomy with established process, methods. It hardly acknowledges for the strong role of innovation, as “traditional” sectors, such as the complete food sector dominate statistical figures. Numbers for innovation niches, such as technology providers that have an important function for the innovation system and the dynamics of the bioeconomy are comparably small and are consequently hardly visible in aggregate figures. This debate may relate to the different visions of the bioeconomy [4, 5]. While current approaches to measure can be attributed very clear to the resource-based vision that emphasizes the importance of the agricultural sector, criticism arises from proponents of a more technology-based vision, which regard technology advances as major driver of the bioeconomy.

Consequently to the current total inclusion of traditional sectors, the bioeconomy is hardly showing dynamics in existing analysis, as the “traditional sectors” usually face moderate growth and declining employment. According to the JRC [24] the number of people employed in the European bioeconomy fell by 1.7 million between 2009 and 2015. Based on similar methodology, [23] even assess a fall from 21,4 million employees in 2008 to 18,5 million employees in 2015. Hence, the question arises, how to interpret this development? Is the economic and political importance for the bioeconomy declining or is a different or additional focus needed to adequately as the importance of the bioeconomy, e.g. a more dedicated focus on innovative growth areas in the bioeconomy? However, one should bear in mind that also in the traditional sectors, new possibilities but also demands for innovative solutions arises. Examples are the transition of the pulp and paper industry to the bioeconomy and building up of related biorefineries and using of new resources (e.g. grass). Hence, in the current article we take a broad view of sectors and do not concentrate on certain “innovative or research-intensive” ones, but will aim to analyse sectoral differences to provide a more detailed view of the bioeconomy. A related challenging issue for innovation measurement is the high heterogeneity of the bioeconomy. The described sectors differ considerably regarding type of products, stage in the value chains, maturity of bio-based products, volume and prices of products, etc. [25]. Hence, to understand the evolution of innovation in the bioeconomy measurement has to provide an assessment about the general innovation development in the bioeconomy, but it should be able to provide insights on structural patterns inside the bioeconomy complex as well. Innovation indicators may complement aggregate economic indicators for the total bioeconomy and shed light whether the political-economic importance of the bioeconomy is really declining.

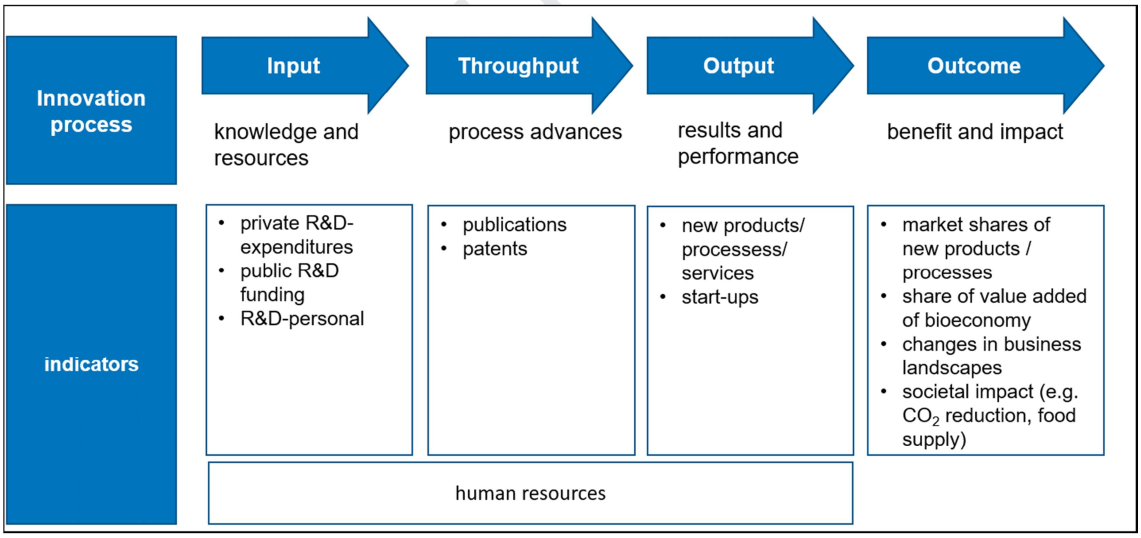
2.2 Measurement of innovation indicators

According to the current OECD OSLO Manual [26], which presents a common basis for OECD countries to measure innovation, the term innovation is defined as follows: “An innovation is a new or improved product or process (or combination thereof) that differs significantly from the unit’s previous products or processes and that has been made available to potential users (product) or brought into use by the unit (process).” This current definition broadens the scope compared to earlier OECD definitions by less focusing on technical innovations and widens the potential usage outside the economic market.

The innovation literature commonly distinguishes between different stages of an innovation process, beginning with inputs (resources for an activity), activities, outputs (what is generated by activities), and outcomes (the effects of outputs) [26]. While such a logic model provides a simplified, linear relationship between resources, activities, outputs and outcomes, refinements to the model include multiple feedback loops etc. are principally possible.

Along, the innovation process, there are some well established indicators that are suited to provide valuable insights [27–29]. The figure below summarizes some indicators that would provide basic information about the current status of the innovation process in the bioeconomy. It has to be emphasized that rising attention in innovation measurement is to attached to the socio-economic impact of innovation. While there are strong expectations toward the impact of innovations, innovations are not good per se [30, 31]. Although innovations are often advantageous at least from a microeconomic perspective the impact on other dimensions can be different. This is a crucial issue for the bioeconomy as there is a high consent that bio-based innovations are not generally advantageous. E.g. Wesseler and Braun [2] state for bio-based products. "The possibility of producing and consuming new products may have positive or negative impacts or negative impacts on human health and/or the environment. Some of those might even be irreversible". Consequently, measurements should include set of economic, ecologic and social criteria.

Figure 1: Potential innovation indicators along the innovation process



In the following, we will first discuss the more common innovation indicators before turning to open gaps in the discussion section.

3. Innovation indicators for the bioeconomy

3.1 Research and development (R&D) activities

Research and development (R&D) activities are an important input for innovation. Not all innovation is based on R&D, but R&D is usually an important prerequisite for successful innovation. Therefore, it is essential for an analysis of innovation activity in the bioeconomy to also include the related expenditure and personnel. A distinction can be made between public R&D expenditure and R&D expenditure by companies in the bioeconomy [32].

Regarding public R&D spending have been only few activities towards the specific measurement of the bioeconomy. E.g. in the German classification for national public spending ("Leistungsplansystematik des Bundes") the R&D spending, in terms of institutional funding for research institutes as well as project based funding is included. According to the Federal Report on Research and Innovation, federal R&D expenditure for the bioeconomy amounted to around 220 million euros in 2011 and has since risen to 273 million euros in 2017 [33, 34]. Moreover, there is a separate category for food and agriculture with R&D expenses to around 598 mio € in 2017 [34]. When those expenses are added, the bioeconomy accounts to around 5 % of the public R&D expenses in 2017. However, international classifications such as NABS 2007 to capture socio-economic objectives does not contain bioeconomy explicitly, and distinguish between agriculture, energy, etc..

Regarding private R&D there are well established statistical sources. However, as they are based on traditional sector aggregation, the challenge regarding attribution to the bioeconomy arises for those sectors, that cannot be counted in total to the bioeconomy. While one approach might be the use of bio-based shares, this may be inappropriate for R&D estimations, as many innovations concern products or processes in high-value added segments, where the amount and price feedstock plays a minor role. An alternative are the respective bio-based share in patents per sector, which is more in –depth explained in the section below. This can be only regarded as a rough assessment as it assumes a linearity between R&D and patent intensity. An indicative pilot test based on historical data from 2010-2012 for bio-based patent share per sector - based on the methodology described in the next section - extrapolated for more current R&D figures to 2015 shows the following. While the shares are estimated on NACE level three-digit codes, the results are presented on the first-digit level.

Table 1: Private R & D expenditure in the bioeconomy in million euros, 2015

Code	Economic area	R&D total	Bioeconomy share	R&D bioeconomy
A	Agriculture, Forestry and Fishing	238	100%	238
C	Manufacturing	67.705	2,7	1.846
D,E	Electricity, Gas, Water Supply; Sewerage, Waste Management, etc.	210	1,5	3
F	Construction	86	0,4	0

J	Information and Communication	3.481	0,2	8
K	Financial and Insurance Activities	308	12,4	38
M	Professional, Scientific and Technical Activities	5.324	4,2	225
Total		**77.114**	**3%**	**2358**

Quellen: [35], PATSTAT, ORBIS

Another approach has been conducted by [36]. They use the official R&D survey conducted by [35] and apply a specific estimation approach for R&D topics. The survey for 2015 comprises additional questions to attribute the activities and related internal R&D expenses to one or more segments of the German "Leistungsplansystematik". [36] use the answers and develop an estimation method to conduct a one-to-one attribution of R&D expenses to those segments. They estimate the internal R&D expenses to 1,2 million € to the bioeconomy. It has to be remarked that the internal R&D expenses comprise to around 75% of all R&D expenses, used in Table 1. While this approach may enable to attribute more directly the R&D expenses to fields such as bioeconomy, it is yet unclear to which extent the firms are aware of the concept and statistical boundaries of the bioeconomy and respond uniformly. This might be an explanation for the lower estimates of [36] compared to the patent share based approach.

3.2 Bibliometrics and patents

Bibliometrics assesses quantity, quality and impact of published scientific literature, which is a key social mechanism by which scientific knowledge is embodied and transmitted [27]. In the current context statistical analysis of scientific publications and their citations provides an opportunity to monitor the performance of the science and innovation system over time and in comparison with other countries or to monitor the emergence of selected themes. It provides an overview of thematic research of companies and academia. On the downside, scientific publications reflect a scientific advance that but cannot necessarily or not directly be commercially exploited. To conduct bibliometric research, various literature and citation databases are used (e.g. Scopus, Web of Science). The more precise identification of literature in the field of the bioeconomy or its sub-areas may be done with a combination of journals/books and keyword searches (title, keywords, abstract, book series, etc.). However, while principally feasible, there have been to the knowledge of the author no attempts to operationalize and analyse bibliometrics for the bioeconomy yet. Existing bibliometric reviews include research that provide a discussion of the bioeconomy [4], but do not cover the probably much high number of technical research results. It has been also out of scope here for this research to elaborate a suitable classification for bioeconomy here, but can be regarded as an important activity for the future.

Patents have a closer connection to the commercialisation or economic exploitation of inventions. Patent applications refer to inventions in the technical field, which are new and for which an industrial application interest of the applicants is assumed. This is because they grant their owners temporary protection against competing developments and are thus an industrial property right. The filing of a patent application involves considerable costs. It can therefore be assumed that a patent application is usually filed when a profit expectation is associated with the patent. Moreover data tends to be objective and reliable, as they represent a census and not a sample, so it does not contain any distortion in the response behaviour, e.g. in surveys. Of course, patent indicators also have their limitations [28, 29, 37], such as

- some innovations are not patentable. While patents are usually fine indicators to measure activities and its results regarding research-intensive, technology-based innovations, other types of innovations, such as service innovations, architectural innovation the (reconfiguration of existing product technologies) or social innovation are dismissed. The latter is frequently discussed in the bioeconomy, such as urban gardening [38];
- some (patentable) market-relevant innovations are not patented. Thus many innovations are protected by other mechanisms (e.g. operational secrecy, speed in development or marketing, etc.);
- Patent propensity varies across sectors/industries and applications and over time.

These limitations of meaningfulness has to be taken into account when interpreting the indicators. Moreover we agree with [37] regarding: “Although patent indicators do reflect an important part of the overall innovation process, for a number of reasons they should not be used in isolation. They show only one aspect of innovation so that a consistent picture of technological change can only be achieved by combining several indicators.”

Based on first existing attempts in literature to delineate bioeconomy or biotechnology in patent statistics we conducted an expert assessment to. We take a broad definition goes beyond existing exercises from [39] and [32], who focused only on the production and use of biological resources.

First, we include patents relating to products or process with the use of biological resources aand second apparatus and methods for processing biogenic biological resources. The former group is related to the well accepted OECD definition of biotechnology [40], but complement it with several non-biotechnology use of biogenic resources, e.g. the use for cellulosic for pulp and paper or patents related to the sugar industry. We include a very few IPCs from the medicine area related to biotechnologically produced biopharmaceuticals, as those match to our taken definition of the bioeconomy as processes of biological resources such as living or parts thereof. One example would be medicinal preparations containing antigens or antibodies (IPC code: A 61K 39).

The later group of apparatus and methods for processing biological resources contains patent groups such as machinery or other inputs (fertilizisers, medical instruments) that are necessary for the exploitation of bio-based products.

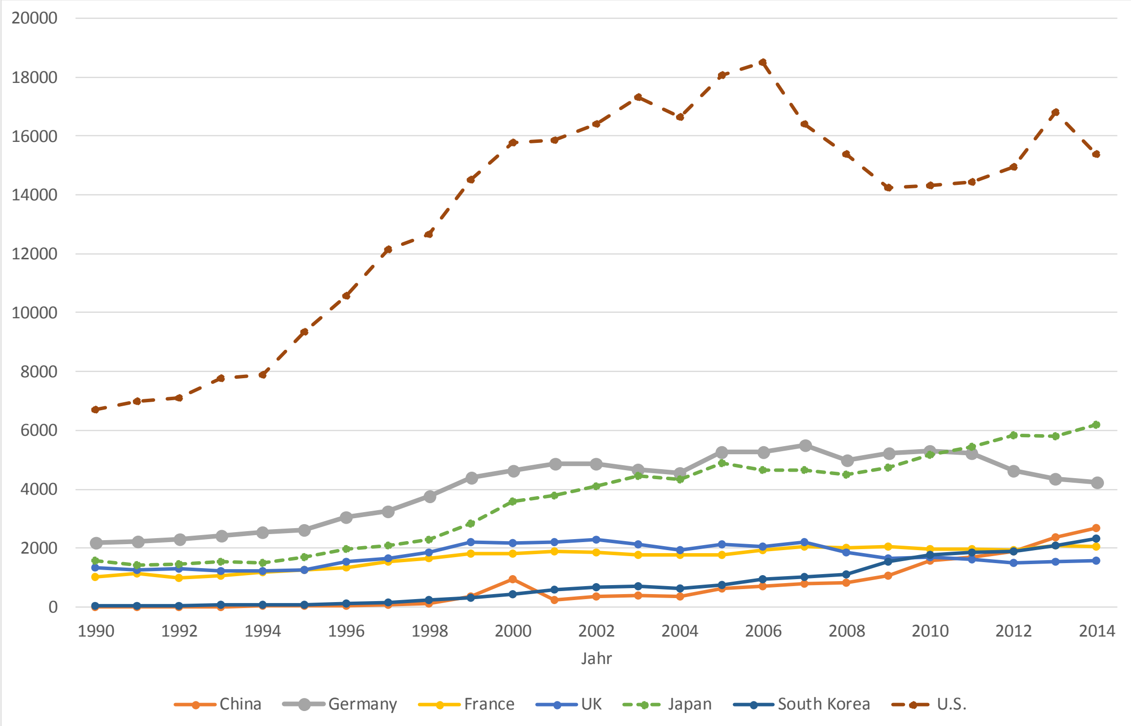
Please note that those IPCs were included that indicate a direct relation the use of biogenic resources. E.g. machines for textiles with out any reference to the feedstock, were not included. A main remaining issue is the inclusion of IPC codes relating to medicine (IPC Code: A 61), which is generally more and more interwined with biotechnology . Thereof we included this IPC class, but nevertheless this may lead to certain overestimations.

The identified IPC codes are listed separately for both groups in supplement table 1. While an assessment has also been performed for the first group separately, we only provide results using the wide definition here to provide a more comprehensive picture on the capabilities in the bioeconomy and getting more aligned with the other innovation indicators.[1] We count patents when at least one of their indicated IPC relates to our bioeconomy definition and do not define additional exclusion criteria in terms of additional IPC codes that should not show up in the patents.

In order to measure patents, the concept of transnational patents appears to be useful. Transnational patents are EPO European Patent Office and PCT (Patent Cooperation Treaty) combined applications and have therefore an international character [41].The numbers show a large growth in patent applications in the 1990s, in particular for the U.S. However, this trend should not be overstated, as an overall increase in patent applications was observed during this period [42] due to a change in patent behavior (for example, increasing importance of patents for licensing). Since the early 2000s, the number of patent applications is rather stagnating with some ups and downs and a steady catch-up of China. In Germany, patent applications decline since 2011. Still, the bioeconomy accounts to around 15 % of the total patents in Germany.

[1] The results for the narrow definition are available on reuqest from the author

Figure 1: Transnational patent applications in the bioeconomy for various countries



Source PATSTAT, own analysis

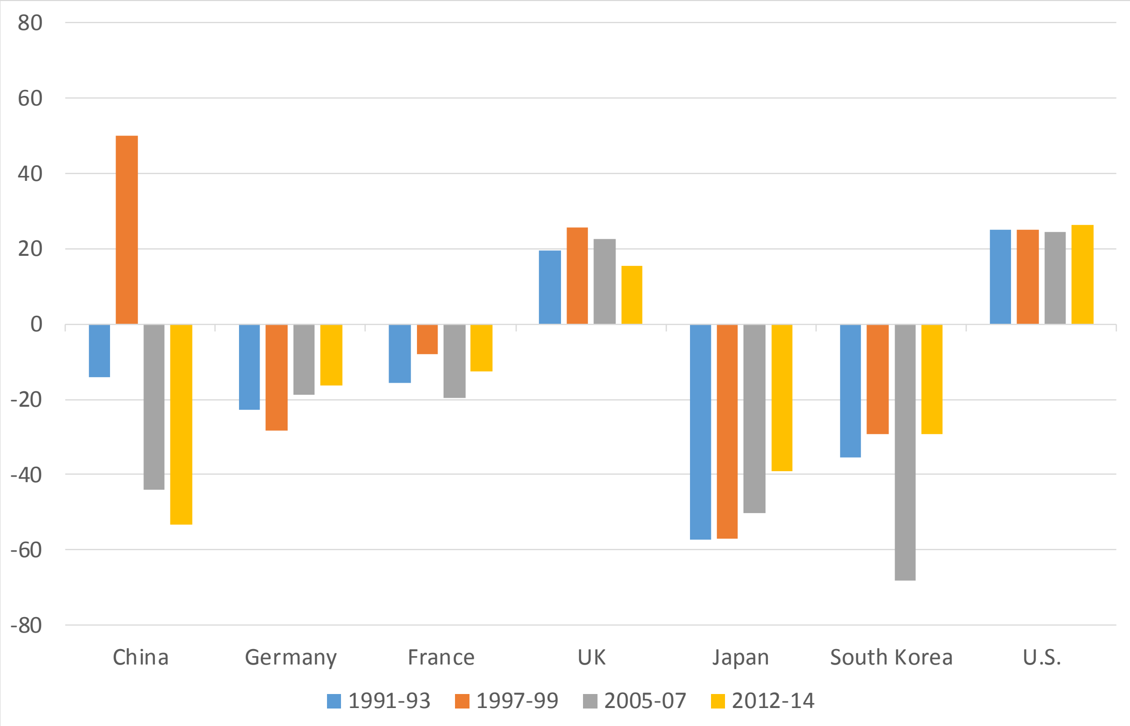
In order to set the patents in the context of total patenting of a country, specialisation patterns reveal how a country's technological focus is set on the bioeconomy To calculate the specialization of countries i on a field j, the following formula is used

$$RPA_{ij} = 100 \tanh \ln [(Pat_{ij} / \sum i\ Pat_{ij}) / (\sum j\ PAT_{ij} / \sum_{ij} Pat_{ij})]$$

The Revealed Patent Advantage (RPA) is calculated by the proportion of a field within all patents in a country relative to the proportion of that field within all patents worldwide. The hyperbolic tangent and the logarithm make it possible for this indicator to move in the range of -100 to +100 with the neutral value 0. Positive values indicate a positive specialization.

UK and the US are positively specialized on the bioeconomy, while in Germany the values are slightly below average, albeit with an upward trend.

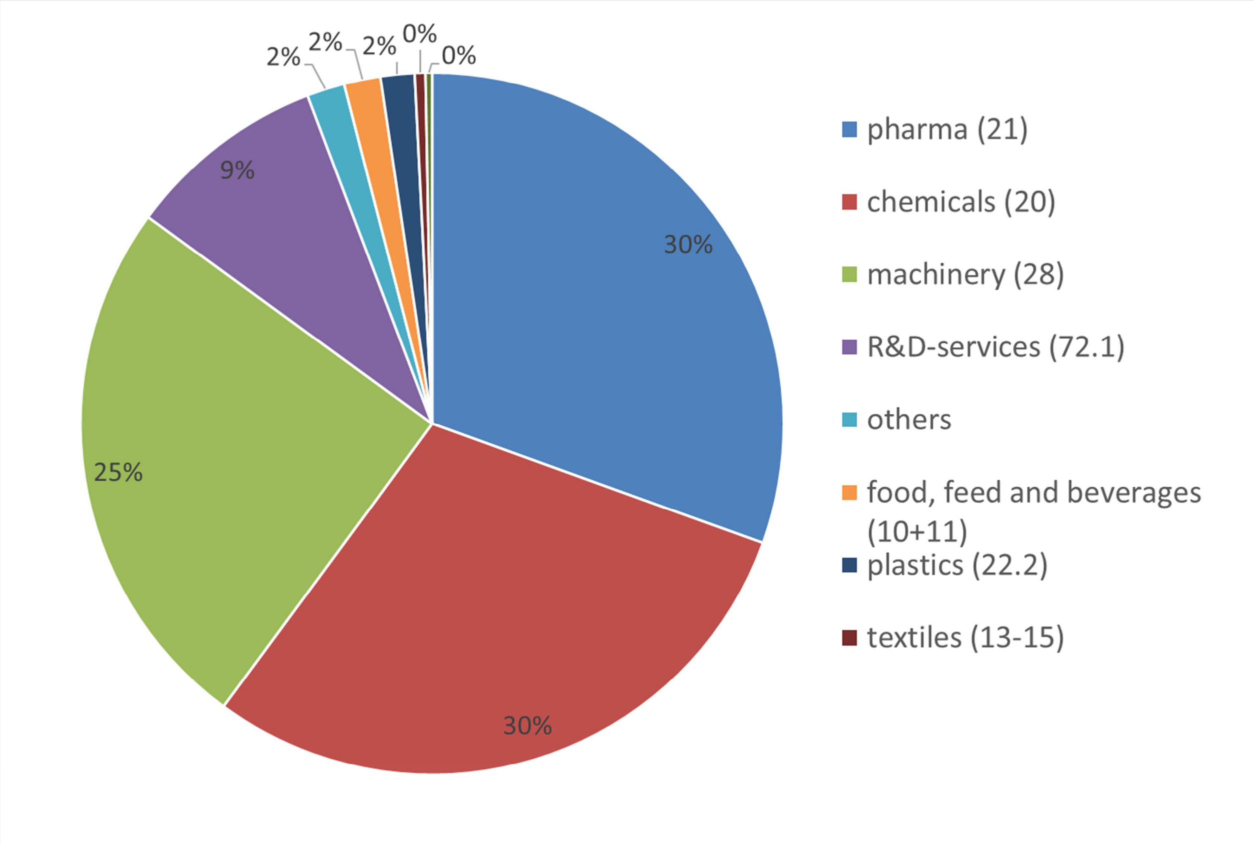
Figure 2: Specialization of selected countries on the bioeconomy for transnational patent applications



Source PATSTAT, own analysis

Additionally patents may be attributed to economic sectors. Such approach allows to track the importance of the bioeconomy in individual sectors. Alternatively, the shares of certain sectors in total bioeconomy patents reveals the importance of different sectors in innovation in the bioeconomy. There are different approaches to link technologies to sector, such as the use of the concordance tables. Here, we use instead a link of a patent database (PATSTAT) to a company database (ORBIS). This link enables to assign patenting firms to NACE sectors and subsequently building shares of total patents for a sector or attributing the bioeconomy patents to sectors. The results of the share approach are depicted in figure 3. It shows that the chemical, pharmaceutical, food and the machinery sector are the sectors with the highest patent shares.

Figure 3: Shares of different sectors (NACE rev. in brackets) in total bioeconomy-related patents in 2010-2012



Source: Fraunhofer ISI auf Basis Patstat und Orbis

The case of machinery or R&D services show that also sectors that are usually classified outside of the bioeconomy may have an important role as technology provider. Moreover, from a German perspective it is interesting that sectors, in which Germany has a strong industrial base such as machinery and chemical industry are key drivers of the bioeconomy.

3.3 Human resources

Human capital is thought of as an input to the innovation process, and in more evolutionary perspectives, as a key output of policy initiatives, insofar as improving human capital is central to an innovation system's capacity to absorb technological and scientific knowledge [27]. It cannot be classified directly in a certain stage of the innovation process, as qualified personnel is necessary to develop new innovations as well as to apply new innovations and commercialize business. Hence, e.g. the European Innovation Scoreboard [43]classifies human resources as framework condition.

Standard indicators for human capital include the stocks and flows of those employed in R&D activities, of graduates in scientific and technological fields, of scientists and engineers, of those employed in specific ‘high technology’ sectors or share of high skilled workers in certain sectors. Moreover, the number of students, first-year students and graduates in bioeconomy-relevant courses can be used to estimate the availability of highly qualified staff in the bioeconomy. Shares of bioeconomy-relevant figures in total figures allow statements to be made as to the extent to which bioeconomy is considered important in Germany's education system.

For that purpose study courses are distinguished whether they have a high relation to the bioeconomy, have some relevance for bioeconomy, but also non-bioeconomy activities, or they have no relation at all. E.g. we included courses such as biotechnology, bioinformatics or agriculture as fully relevant, while e.g. chemistry or regenerative energies as partly relevant. Based on such classification, table 2 depicts the distribution of students in the bioeconomy for winter semester 2016/2017 in Germany. The numbers show that approximately 6% of all graduates, students and first-year students are directly attributable to the bioeconomy, approx. 12% to courses of study that may be partly relevant for the bioeconomy. The high latter figure is mainly due to the high numbers in mechanical engineering, industrial engineering and chemistry.

Table 2: Students and graduates in bioeconomy-related courses in Germany (winter semester 2016/2017)

	Fully bioeconomy relevant	Partly bioeconomy relevant	total	Percentage of fully bioeconomy relevant	Percentage of partly bioeconomy relevant
First-year students	29.114	52.460	43.5427	6,7%	12,0%
students	173.845	333.003	2807010	6,2%	11,9%
Graduates	33.913	61.252	491.678	6,9%	12,5%

Source: Own calculations, based on Statistisches Bundesamt, Fachserie 11 Reihe 4.1 und Reihe 4.2

To measure skills, suitable approach data source is the use of occupational group classifications based on the employment statistics of the Federal Employment Agency, according to the current German Classification of Occupations. Here occupational groups are determined at a relatively low level of aggregation, so that the bioeconomy can be distinguished rather precisely. Moreover, the classification of occupation differentiate the skills in for different qualification requirements. Again, a distinction is made as to whether these can be fully or only partially attributed to the bioeconomy. An empirical analysis shows that the proportion of skilled workers dominates. This is due in particular to the professions of agriculture.

Table 3: Distribution of the requirement level in occupational groups with relevance to the bioeconomy in % (date of 30 June 2017)

occupational groups	assistant	Skilled worker	specialist	expert
fully bieoconomy relevant	29,5%	64,1%	3,2%	3,1%
partly bioeconomy relevant	29,7%	58,5%	6,9%	4,9%
total economy	15,6%	58,7%	12,8%	12,9%

Source: [44]

3.4 Commercialization and impact of Innovation

While R&D activities, education and patent applications are input and throughput indicators in the context of innovation activities, they do not reflect the outcome of innovation efforts. Especially for innovative areas of the bioeconomy (e.g. bio-based chemicals) it would be important to know to what extent innovations are actually entering the market, to what extent they diffuse on the market and how they impact economy and society. Additional output indicators (e.g. number of newly introduced products) or outcome/impact indicators (e.g. changes in the corporate structure due to start-ups or closures; growth of the bioeconomy vs. non-bioeconomy sectors, etc.) would therefore be helpful in determining the economic and social significance of innovations [45].

A valuable data source to measure the output and impact of innovation is the use of innovation surveys [26]. As such surveys usually focus on the activities and outcomes for a certain innovation agent and does not analyse the innovation itself in-depth, it is classified “subject” approach in innovation literature [29]. The survey collect firm-level data about their processes of innovation, such as the inputs for innovation (knowledge etc.), sources of ideas, users of innovation, obstacles, output, etc. [29]. In Europe, the Community Innovation Survey is well established since the early 1990s and many EU countries participate voluntarily. The survey covers sectoral levels and disclose activities mostly on a NACE 2 digit code. As explained earlier this aggregation level is not sufficient to identify bio-based activities in those sectors that are only partly attributable to the bioeconomy.

Another related possibility is the "object" approach that focuses more on certain (technological) innovations [29], which may comprise various sources about innovation such as reviews in scientific publications market studies, company press releases, information about patent applicants, current R&D projects etc. in combination with expert interviews for selected areas of bio-based innovations.

One approach is the measurement of a key indicator for innovation or diffusion connected to registrations for regulatory purposes. This is well established for assessments in some innovative fields: E.g. in the biopharmaceutical field, the well countable indicator of new molecular entities approved by regulatory institutions such as the U.S. Food and Drug Administration has become a well recognized indicator for biopharmaceutical innovation. As the number of products is limited and market studies for single products available, the share of turnover of biopharmaceuticals can be estimated rather well. As another example, electrical mobility the number of new registered electric vehicles in a country has become an important target.

However, availability of comparable data for bio-based products is rather limited. A particular challenge for measurement is the heterogeneity of bio-based products. Product groups significantly differ regarding whether they comprise many different products/ product formulas or a few one, whether they are low-volume, high-price products vs. high-volume, low-price products, whether new products with new functionalities are relevant or drop-ins with identical characteristics to fossil-based chemicals exist [25]. These differences influence whether techno-economic indicators such as product announcements, market volumes etc. are feasible and comparable indicators.

There have been several studies commissioned by the Joined Research Centre or DG Research and Innovation. European Commission regarding the market uptake of bio-based products, with an assessment of the status quo, but also forward looking character [46, 47]. These studies provide assessment of current technological readiness scale in combination with market outlook for promising product developments. These efforts provide detailed information about the most important innovations from a market size perspective and provide stakeholders orientation about the current status and potential ex-ante impact. These studies complemented by bio-based industry and market studies commissioned by the Joint Research Centre [46, 48]. However, the latter studies provide only limited information whether the innovations are finally adopted widely in the market and do hardly cover innovations on niche markets and can be hardly updated.

Looking at the results, [46] identified 94 sugar-based products, with some already commercial, the majority at research/pilot stage, and only a few demonstration plants crossing the “valley of death”. For a selection of ten promising key platform chemicals a high potential of GHG savings is identified and for some even the potential for cost reduction, however the subsequent downturn of the oil price couldn’t be considered at that time. [47] mapped innovative bio-based products from urban wastes and biomass apart from sugar platform. They identified 107 innovations One-third of the products are approaching full availability on the market, however only a few of the other products are in a development stage close to commercialization, but mostly in an applied research stage (technological research scale 5).

Moreover, current market outlook in key bio-based chemicals for the next is rather mixed, estimate the yearly growth rate for bio-based chemicals of 3,6 % until 2025 [48]. Such figures indicate a tough environment for introduction and adoption of innovative products and processes.

4. Discussion and ways forward

The results show that there are significant innovation activities in the bioeconomy and available human resources, which is not a completely few phenomena as the bioeconomy comprises segments (agricultural research, food, pulp and paper) that were well developed before. There are innovations in the pipeline for novel applications that currently use fossil-fuels, however there are indications that the market impact is yet limited.

Table 4 summarizes for those presented indicators where it is possible the latest share of the bioeconomy of the total economy for Germany. The numbers indicate that the private R&D expenses for the bioeconomy are rather low, while the other figures are in the broad range or even higher than existing economic indicators for the bioeconomy in Germany [6].

Table 4: bioeconomy share for various innovation indicators

Indicator (year)	Public R&D	Private R&D	Patents (2014)	Students (2016/2017)
Bioeconomy share in %	5,0%	3,0 %	15,1 %	Fully bio: 6,2 % Partly Bio: 11,9 %

Sources: See various sources in the tables and figures above

From a conceptual point of view, the indicators above show some progress towards the measurement of the bioeconomy, but also challenges to measure the targeted phenomenon adequately. E.g., still some debatable questions about the delineation in patent statistics prevail. Besides those indicators, there are additional challenges, but also several ways forwards in the measurement of innovation of the bioeconomy. This concerns the definition and goals of the bioeconomy, type of indicators, data sources, international harmonization of concepts and the time frame of analysis:

First of all, it has to be stated that the definition and subsequently the goals of the bioeconomy are still disputed. In particular, the goals encompass different sustainability dimension leading to the question, whether the value of the bioeconomy should be defined beyond pure economic terms.

One starting step for a conceptual differentiation with more relevance to different impact goals is the segmentation regarding purposes of innovation. [14] differentiate between four so-called transformation paths, which differ in types of dominating innovation:

- *substitution of fossil fuels with bio-based raw materials*: Innovation that focus on the substitution of existing products without changing the functionality of products (drop-in products)
- *Boosting primary sector productivity*: If technological innovation increases productivity in agriculture, forestry, or even fishing, it can release transformative forces that open up new production methods or locations.
- *New and more efficient biomass uses:* Innovation in downstream sectors often aims to increase the efficiency of biomass use and waste stream recycling.
- *Low bulk & high value applications*: Innovations in those area usually provide superior functionalities than fossil-fuel based counterparts (e.g. less toxicity) and may use only small amounts of biogenic resources. Hence, the substitution of fossil fuels to biomass plays a minor role.

Potentially, indicators or in-depth studies may focus on certain paths or explicitly distinguish between these paths. Here, an additional fifth path would be useful, which acknowledges for social innovations, such as urban gardening or new collection and usage forms of food losses, as technical solutions alone will be not sufficient to achieve underlying goals. Moreover, it has to be reminded that the goals associated with the bioeconomy may change over time. While in the beginning of the 2010 decade the substitution of resources were defined a major goal of the bioeconomy, the potential contribution of the bioeconomy to broader sustainability goals has gained increasing importance.

Based on current definitions, this contribution discusses the assessment of the aggregate bioeconomy, a more detailed analysis of the innovation process regarding actors may be of further interest. Possibilities are the analysis of actor networks by analysing co-patents or the study of technology and industry convergence by combining patent data with additional sources (e.g. firm data for merger & acquisitions) [49]. Moreover, the integration of innovationindicators in model-based forward-looking analysis (e.g. [50, 51]) is an important step to link past developments with future pathways [17].

Regarding missing indicators, the analysis shows there are clear gaps in outcome and impact indicators. Generally, there have been increasingly efforts to measure economic, social and sustainability implications of the bioeconomy. While they have links to innovation activities, they help to understand the implications of the bioeconomy in general. E.g. various countries commitments towards the measurement of SDGs and bioeconomy may create synergies [3] .In order to understand the dynamics of the bioeconomy, additional efforts would be helpful to elaborate indicators that are suited to measure the postulate postulated transition to the bioeconomy. As one example, [52] develop a substitution share indicator, that aims to relates bio-based substitute products to their fossil-based counterparts and to accounts for indirect fossil resource flows.

However, to gain more insights in causality and the innovation process more micro-level data would be needed. As explained above, current surveys do not provide an adequate boundary setting to analyse the bioeconomy. This could be principally changed in the future, e.g. by an additional classification whether the responding firms are active in the bioeconomy or not or by adding additional questions similar to environmental innovation, which is a subject in the CIS every few years [53].

Another option would be additional data collecting efforts named under the umbrella of big data – such as web, open and administrative data and their combinations — will provide new opportunities for an adequate innovation measurement. Currently, in particular innovative networks or number of active firms for certain products or processes are discussed in exploratory studies [43, 54]. There are serious questions about the appropriate coverage of heterogeneous fields and data quality, but there may be significant advances and especially development of new indicators and data structure in the future.

A critical issue for further data collection is the ongoing of efforts that aim to harmonize the definition and measurement of bioeconomy, at least across macroregions (such as the EU) that will allow development of structured and comparable measurement and monitoring methodology of the trends in bioeconomy across countries [3] . The empirical analysis in this article focused on Germany. While some of the statistical delineations are directly transferable to the EU-level, there are exceptions such as the public R&D and the education indicators, which are assessed on more detailed national classifications. However, this assessment may serve as a starting point for identifying occupations or courses of studies in other classifications.

It can be difficult to capture the impacts of a new innovation due to a time lag between investments and outcomes[3]. It has turned out that even in the absence of strong regulation, such as in the pharmaceutical sector, the commercialization of bio-based products can last many years. There are significant technological challenges in the optimization and particular the upscaling of-bio-based products. Product properties usually differ by applying living organisms and biogenic resources in contrast to fossil products. This implies that it is more difficult to enable stable processes and product properties. Consequently, long-term assessments are needed to trace the impact of innovation efforts.

5. Conclusion

There are high innovation potentials in the bioeconomy. However, it is unclear whether innovation activities actually rise and result in new products and processes and whether the desired positive impact on societal goals may be achieved. Therefore, an innovation indicator system that enables to monitor the inputs, throughputs, output and socio-economic outcomes of bioeconomy innovation is of high value for policy makers. However, as the general discussions and the analysis for individual indicators shows the information base is still scattered.

According to available data, there are significant private and public R&D funding activities in Germany. However, the patent development and specialization shows that Germany is not highly focused on bioeconomy activities. Interestingly, taking a sectoral perspective a high importance of industries such as chemicals or machinery can be identified. As Germany is rather strong in these industries it may have an advantage in commercialization, if the actors are believing and investing in the potential of the bioeconomy. However, further advances in measuring the innovation impact is needed to shed more light on socio-economic and ecologic outcomes and to include the role of social innovations.

Of course, the innovation perspective is not addressing all policy relevant measurement issues: hence, innovation measurement could be an important cornerstone of a broader monitoring system that observes the economic, social and ecologic development of the bioeconomy. Here innovation indicators shed more light on input activities to develop the bioeconomy, detect early signs of change in the bioeconomy and to enable policy makers to assess the impact of important policy instruments for the bioeconomy. This could be accompanied by taking a more foresight-looking perspective to identify and shape concrete innovations as well as more systematic assessment of the barriers and drivers of innovation (e.g. with innovation maps). If such progress is achieved, the concept to measure innovation may be also of high relevant of other area of cross-sectoral concepts or economic activities. However, the adequacy of transfer should not be taken as granted, as potential drawbacks or challenges of delineation may be more severe or at least different in other contexts.

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Funding:

Funding: This work was supported by the German Federal Ministry for Economic Affairs and Energy technology by commissiong the study „Elaboration of Economic Indicators for Monitoring the Progress of the Bioeconomy (Bioeconomy-Monitoring)“

Acknowledgements: I thank Prof. Dr. Ulrich Schmoch (Fraunhofer ISI) for his support regarding the patent analysis. Moreover, I thank Dr. Johann Wackerbauer (IFO Institute), Wiebke Jander (ATB Potsdam), Dr. Andreas Grundmann (ATB Potsdam), Dr. Stephan Piotrowski (NOVA) for comments reagrding the work during the bioeconomy monitoring project.

Highlights

- Innovation measurement concept for the bioeconomy is proposed
- Germany has significant private and public R&D funding activities in the bioeconomy
- Germany is not specialized in the bioeconomy patents
- Information gaps for the innovation impact prevail

Author statement

I declare that I wrote the full article b myself. See acknowledgements for support in the related research project.

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