
# Where the dandelion meets the road – Location determinants of German bioeconomy patents

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# Where the dandelion meets the road – Location determinants of German bioeconomy patents

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**Abstract:**

The paper at hand provides deep insights into the development of the German bioeconomy at the municipality level. The aim was to find out which determinants play a role in the location of bioeconomy patents at the municipality level and to analyze the respective stages of the bioeconomy in the industry life cycle (ILC). Within the three fields of biomass, biotechnology, and biomaterials, subfields were built through a keyword-driven approach to capture the bioeconomy. We conducted a logit regression model using the following data sets: population density, the area of forestry and agriculture, German Federal subsidy data, topic-specific patents and publications, as well as the overall patent and publication activity. The results indicate that the researched bioeconomy fields are in different stages of their life cycles and that they perhaps change the known structure of the life cycles. It appears that bioeconomy patents rather emerge in rural areas, and that there is only a minor influence of the usage of the surrounding landscape. Most of the subfields show a positive reaction to public subsidies. Furthermore, path dependence is strongly influencing the occurrence of bioeconomy patents. Our research can be used by diverse stakeholder groups, especially federal and local politicians as well as scientists, and contribute to the understanding of the bioeconomy on the so far relatively uncommon, but comprehensive level of municipalities.

**Keywords:** bioeconomy, biomass, biotechnology, biomaterials, patents, publications, subsidies, industry life cycle (ILC), regional innovation systems (RIS), municipality, path dependence

**JEL Classifications:** Q57, Q10, R11

**Highlights:**

- Application of a detailed dataset (acquired by a keyword-driven approach) to a logit regression, showing positive impacts of public subsidies and topic-specific research hotspots
- The development of the German bioeconomy is less concentrated in highly populated municipalities than other innovative activity
- Strong path dependence to former bioeconomy innovations

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**Abbreviations**

| | |
|---|---|
| BMBF | German Federal Ministry of Education and Research |
| BMEL | German Federal Ministry of Food and Agriculture |
| EC | European Commission |
| e.g. | exepli gratia, for example |
| FoeKat | Foederkatalog (catalogue on all German public subsidies) |
| i.e. | id est, that is |
| ILC | industry life cycle |
| IPC | International Patent Classification |
| NGOs | non-governmental organizations |
| RIS | Regional Innovation System |
| SMEs | small and medium-sized enterprises |
| TIS | Technological Innovation System |

## 1 Introduction

What is your tire made of? The dandelion, a flower which is seen as weed by most people, provides a fascinating insight into the bioeconomy: “Approximately 40,000 products of everyday life contain natural rubber. [Researchers] were able to identify a cost-effective and eco-friendly alternative to the natural rubber tree: the dandelion” [1]. Fraunhofer Institute and the global tire producer Continental now work together in the small German village Anklam to produce tires made of dandelion rubber. This research within the field of bioeconomy seeks to reduce the fossil-based products to replace them with fast-growing, natural, bio-based materials. As the example shows, this research is bound to the usual innovation hubs. Therefore, studying the bioeconomy is a good approach to determine the location of innovations in new fields of technological development.

The bioeconomy has rapidly gained attention over the last two decades. Since the turn of the millennium, politics, society, and science have progressively faced the depletability of resources. Developing a (sustainable) bioeconomy is one of the strategies to meet the growing need for resources, to ensure food security, protect the climate, environment and biodiversity and, especially, use the fossil-based resources more consciously. The bioeconomy aims to reduce or at best substitute as many of the fossil-based part(s) of the economy and seeks to use and recycle all used materials. This makes the bioeconomy essential for the future social and economic development as some resources are unlasting [2]. Certain challenges result from this, especially the difficulty to delineate the bioeconomy. The bioeconomy reaches into many branches, sectors, and industries and provides the application and implementation to various products, (production) processes, services, etc. The alteration to a bio-based economy is an essential development for a more sustainable future but it complicates research in this respect. As Wydra [3] states, it is difficult to identify the actors and activities belonging to the bioeconomy as they are related to many crossover technologies. This structure complicates research in the field and simultaneously necessitates and produces various methodological approaches.

To contribute to this discussion and to specifically provide deeper insights into the field of the bioeconomy, patent data is one appropriate way to study innovation activity and its location. While an extensive literature on the location of innovation processes in general, theoretical as well as empirical exists, the location determinants for innovation activity in the bioeconomy have not gained much attention in the field of science. We believe that the specific characteristics of the bioeconomy make it scientifically interesting to study the specific determinants. However, it is difficult to identify the relevant patents because of the crossover character of the bioeconomy. Furthermore, the bioeconomy contains a variety of activities which might also influence the determinants of the location. Therefore, we do not study the entire bioeconomy but focus on various subfields. The main research question of our study is to find out why bioeconomy innovation activities emerge at specific locations: What are the determinants of the location of bioeconomy patents in German municipalities and how do they differ between the various subfields?

The remainder of the paper proceeds as follows: The next section presents the literature background on the bioeconomy, the life cycles of industries, and regional innovation systems. Next the methodology in chapter 3 is presented, which explains how the keywords were selected and which variables were chosen to be part of the logit regression. In section 4 the results are discussed, and section 5 concludes this paper.

## 2 Theory and background

The bioeconomy is seen as one main solution to alter the current (intensive) use of fossil-based, and therefore limited, resources in the worldwide economy. To achieve this aim, not only do the resources and pre-products have to be changed but also the related processes, services, and technologies have to be adjusted [4]. The bioeconomy is based on scientific findings and thus from a political view linked with innovation policies and technology transfer from science to industry and in a second step with economic and employment growth. This has made the bioeconomy rather popular for policy makers in the European Union as well as other countries [5].

Since bioeconomy as a research field entered the scientific, political, and public discourse, many definitions, research and political agendas were published. Capturing the bioeconomy is additionally aggravated by this diversity [6]. Hence, we start with an explanation of what bioeconomy is and how the term originated in Germany. The second part shortly outlines the main idea of life cycles in industries and how these life cycles shape the location patterns in the bioeconomy. The third part of the theory section adds the regional innovation systems (RIS) view to contribute to the small spatial scale we used for our analysis.

### *2.1 Bioeconomy*

The bioeconomy is one possibility to address the great challenges of the 21st century [7]. Despite this key role, it is a relatively new research field and no common but rather various definitions of the term bioeconomy exist. The usage of the term bioeconomy started in the early 1970s when Nicholas Georgescu-Roegen stated that the production of any product comes with a higher biological and economic price compared to the value of the product itself. This inevitably leads to a deficit because the economy cannot grow limitless. Therefore, a proper balance between biological resources and economics is needed: the bioeconomy [8]. Georgescu-Roegen states: “The conclusion is clear and inescapable. The industrial activity in which a very large part of mankind is now engaged speeds up more and ever more the depletion of terrestrial resources. It must, therefore, come to a crisis” [9]. He adds that an answer to this may be found in ecological economics, which led him to the term bioeconomics. Although the term bioeconomy came up earlier, the use of the concept in science started rising in the early 2000s [10]. Within the last ten to twenty years definitions became at the same time wider and more specific. While Georgescu-Roegen describes the underlying processes, recent definitions like the one from the European Commission seek to include more but rather unspecific details: “The bioeconomy […] encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy. Its sectors and industries have strong innovation potential due to their use of a wide range of sciences, enabling and industrial technologies, along with local and tacit knowledge” [5]. Within this concretization, the production processes are mentioned, the products themselves play an important role as well as energy coming from renewable materials. Moreover, the diverse and crossover character is emphasized. Bioeconomy is not just one sector or industry but covers many of them, and, as the main aim attempts to substitute non-renewable resources as much as possible. Hence, this concerns not only the sectors like chemistry, pulp and paper, or the food sector [3, 11] but many various branches, which makes it difficult to research on the one side and interesting and diverse on the other. Whereas some sectors can be completely attributed to the bioeconomy as a whole (e.g., food and beverages, agriculture) [12, 13], some account for a share such as the manufacture of textiles or bio-based plastics [14].

The German Federal Government’s definition is similar to the one of the European Commission but specifically stresses the focus on the potential of bioeconomy innovations and the systematic approach. Hence, we will use the following definition of the German government in this paper because its focus on innovation fits our approach best:

> “The German Federal Government defines the bioeconomy as the production, exploitation and use of biological resources, processes and systems to provide products, processes and services across all economic sectors within the framework of a future-oriented economy. Innovations in the bioeconomy unite biological knowledge with technological solutions and utilise the inherent properties of biogenic raw materials such as their natural cycles, renewability and adaptability. The bioeconomy harbours the potential to provide new kinds of products and processes that protect natural resources and ensure our future prosperity” [6].

The bioeconomy came up in the early 2000s, following a line of strategies and papers concerning the biotechnology [15, 16]. Worldwide, Germany filled one of the leading roles in establishing a Bioeconomy Council and developing a national bioeconomy strategy [3, 17]. German Federal Ministries set up a funding program together to support the innovation and innovative ideas of small and medium-sized enterprises (SMEs) [6]. The Federal Ministry of Education and Research and the Federal Ministry of Food and Agriculture strongly promote their bioeconomy support programs since 2010. The particular focus of these support programs is on (basic) research and SMEs [6]. According to their strategy, SMEs play an important role in the innovation of the German bioeconomy. Not only the society is responsible to implement and accept new economic ideas. Furthermore, the economy has to change, which includes besides the development of new materials or technologies also alterations of different steps within the production processes. Consequently, this could also change the life cycles of firms and products as a whole. Hence, insights into the affected structures are crucial as well as the analysis of the dynamics of innovation in bioeconomy-related fields [11].

### *2.2 Life cycles*

The literature on industry life cycle theory addresses the aforementioned dynamics and changes in ageing industries [18]. It analyzes the stages an industry goes through and provides the opportunity to research different statuses of the bioeconomy. In the literature, there are three, respectively four, stages of a stylized product life cycle [19, 20] which can be, according to Klepper [19], applied to the industry life cycle.

The first stage is the "exploratory or embryonic stage" [19] where after a gentle beginning many firms enter the market with unspecialized products and machines [21]. Uncertainty on both sides, consumers and entrepreneurs, is high. The firms with their new product do not have many customers, and firms compete for (product/service) innovation. The density and diversity of actors are high: "in a young industry there is considerable diversity in the research and development (R&D) activities of firms and in the innovations that they produce" [18]. Abernathy and Utterback [21] also assign great influence on the innovation process to smaller companies in this period because they are more agile and have high adaptability. The German Federal Government supports start-ups to help them compete within this phase of their life cycle [6].

Stage two is the "intermediate or growth stage" [19], in which the products and machines become more specialized whereas the level of innovativeness decreases. Fewer firms enter the market and sometimes new standards evolve [21, 22]. An example within the German bioeconomy for this stage is the process of "precision breeding" [1] of the dandelion plant from the Fraunhofer Institute. Scientists discovered the valuable rubber within the dandelion (first ILC-stage), researched different dandelion species and then specialized in the Russian dandelion because it naturally contains more rubber. They entered the second stage by being “quickly able to double the amount of natural rubber in the Russian dandelion” [1].

The third stage is called the “mature stage” [19] where the market steadily stabilizes [21]. Fewer firms compared to the second stage enter the market, fewer innovations are developed, and the focus changes from product innovation to process optimization. Klepper puts it shortly: “initially the market grows rapidly, many firms enter, and product innovation is fundamental, and then as the industry evolves output growth slows, entry declines, the number of producers undergoes a shakeout, product innovation becomes less significant, and process innovation rises” [19].

The fourth stage is mentioned in the later industry life cycle literature and concerns the decline or exit of the industry [20, 23, 24]. Here, the market size declines up to a certain point and the number of firms stagnates or decreases. The consequence is either a relatively stable market or a dissolution. Exemplarily for the third and the fourth stage is the field biomass. One of its main sectors is agriculture which exists since the beginning of human sedentarism and is still one of the most important parts of the economy and the bioeconomy because it is the main producer of biomass. Agriculture, together with food and beverages, generates an annual turnover of 1444 billion € and employs more than ten million persons in 2012 in the European Union [25]. The production of biomass is seen as a traditional sector and can therefore be assigned to the mature stage with rather incremental innovations. Whereas the production of biomass for particular uses like within biomaterials or biotech could still evolve within the second ILC stage [25].

This is a stylized pattern and deviations are not only common but somehow normal as there can for example be continuous ongoing innovation also in the last stage. Markard concludes: “the ILC literature highlights competition and shakeouts together with the shift from product to process innovation as key features of the industry life cycle” [20]. As a result, the industry life cycle theory is used to explain the development and evolution of various industries. Brenner and Dorner discuss the question of whether the industry life cycle framework applies to all industries and conclude, that “the life cycle patterns documented for (product) industries in extant literature may be generalized to other nonmanufacturing industries including services” [24]. Thus, since there is the possible applicability to any industrial sector, also bioeconomy processes with their inherent diversity can be considered to have a life cycle as shown above. In this respect, the existing life cycle literature is despite or even because of its variability applicable to the bioeconomy. Consequently, all parts and processes of the bioeconomy have to be included and not only the development of the product plays an important role. But also the development of technologies and services and in case of the bioeconomy the establishment of an integrated circular economy matter. Applying the life cycle concept to the bioeconomy as a whole is impossible because different parts of the bioeconomy are at different stages of their development. Therefore, we propose to consider ILC developments within the bioeconomy separately as the bioeconomy is too heterogeneous to be studied as one subject.

### *2.3 The regional dimension of the bioeconomy*

In recent times, also a rich body of literature was evolved concerning the technological innovation systems, which is partly based on ILC literature. Technological innovation systems (TIS) include not only companies but also a set of various actors like institutions, non-governmental institutions (NGOs), and even more impalpable factors like regularities, standards or social norms [20]. However, the TIS concept considers the different functions of such systems, while we focus on patents only. Therefore, the TIS concept is too broad for the paper at hand. The Regional Innovation System (RIS) concept has a stronger focus on the generation of innovations, which is of greater interest for our paper. The existing research covering RIS has shown how important local factors are for innovations and new business development (see, e.g., [26, 27]). The RIS approach emphasizes that any company is embedded into an environment consisting of the institutional set-up, the available workforce, physical distances to feedstocks, knowledge institutions, and customers among others. Since the local circumstances are more or less favorable to a specific industry, the geographical concentration of certain industries as well as innovative activities can be observed. Despite the increased digital availability of knowledge, spatial concentration intensified over time [28]. This was investigated in particular for the biotechnology industry [29]: Biotechnology clusters emerged, among other places, in Philadelphia and New York, and related chiefly to the historically built presence of the headquarters of the nation's largest pharmaceutical manufacturers. One important mechanism behind the clustering is the exchange of tacit knowledge: While codified knowledge is easily accessible, tacit knowledge is created, disposed and disseminated through personal interaction (see [30, 31]).

Considering this theoretical background and the fact that the subfield biotech and biomaterials are relatively new scientific and political fields, we expect innovations in these fields to be located more in populous areas than other innovative activities. We expect to find biotech and biomaterials innovations in metropolises as well as scientific and industrial hotspots because the knowledge flows exponentiate there. The biomass subfield is in the mature stage of its life cycle and depends strongly on natural resources. Therefore, we assume that innovations in this field are more likely to be found in less populous and less scientifically-focused areas than other innovations. Hence, we derive the following hypothesis:

*H1a: We expect innovation activities in the more recent fields like biotechnology and biomaterials to* *be more frequently located within cities than other innovations, whereas innovations in the more agricultural-related field biomass are located more frequently in less populous areas compared to other innovations.*

In line with the previously mentioned arguments and due to the resource requirements of the biomass we also expect to find the following:

*H1b: A bigger amount of surface used for agriculture and forestry is negatively linked to most subfields of the bioeconomy, especially for research-driven fields like biotechnology but positively linked to the subfield of biomass, especially the share of agriculture.*

Furthermore, innovation policy influences the type and the frequency of the innovation processes that then eventually lead to patents. Regional governance includes on the one hand by private representative organizations like industry associations or chambers of commerce and on the other hand by public organizations such as regional agencies which provide innovation support [32]. In the case of the bioeconomy, access to funding is of utmost importance since it is a science-based industry with often long procedures from first research findings to commercial products. An example of this in biotechnology is genetic engineering, which always had been a promising industry but people still had to wait a long time for commercial successes [29]. In the case of the German bioeconomy, governmental (innovation) funding is provided mainly by two national agencies, the Federal Ministry of Education and Research (BMBF) and the Federal Ministry of Food and Agriculture (BMEL). The aim of the German bioeconomy research strategy, the interdepartmental National Research Strategy Bioeconomy 2030, is a circular, sustainable, bio-based economy [13]. To reach this, projects are funded, as well as (international) project cooperation, foundations of small and middle-sized firms, infrastructure measures, research and development [33]. If the funding of bioeconomy innovation projects was effective, we would observe enhanced bioeconomy patenting activity in the regions where the funding was provided. Hence, we expect the following:

*H2: The amount of funding a region received in the respective technology is linked with its patenting activity in the same technology.*

The embeddedness of innovation means that it is highly path dependent (for an overview see [34–37]). Usually, new economic activity in a region evolves from former activity. For completely new technological developments, related variety is known to contribute to and create regional economic growth [38]. In the second stage as well as later stages of the technological life cycle, it tends to be assumed that innovation success breeds further innovation success. An investigation of the bioeconomy should therefore consider at former similar activities. Since the studied fields are assumed to be in the second or third stage of their life cycle, we hypothesize the following (in line with [29]).

*H3a: Former patenting activity in each bioeconomy subfield is positively linked to recent innovation in this bioeconomy subfield due to path dependence.*

Although the bioeconomy is quite interwoven with other parts of the economy, technologically it differs and often follows different paths. Therefore, the bioeconomy builds its regional innovation systems instead of connecting to other fields within the overall technological activity:

*H3b: Overall patent activity is negatively linked with innovations in the bioeconomy.*

When distinguishing between industries with a synthetic knowledge base versus an analytical one [39], the bioeconomy, at least biotechnology, has a rather analytical knowledge base [31]. Industries with an analytical knowledge base usually rely on close links to universities and research institutions, i.e., they have many joint research projects. Industries with a synthetic knowledge base receive innovative ideas predominantly from interaction with customers or other users than from scientific research. Again, we can expect spatial proximity to be of great importance for the circulation of knowledge. Knowledge spillovers will happen first, fast, and most accurately within the local social networks of the actors involved [31]. This happens even before findings are published and hence become codified analytical knowledge. Storper and Venables [40] call this phenomenon the "local buzz" which fosters the clustering of industries. Furthermore, failures, discussions, and unproductive lines of research might not be published, but can still be considered valuable local knowledge.

*H4a: The amount of publication activity in the respective subfield in a region is linked to enhanced bioeconomy innovations, especially in the field of biotech, where we expect to have a strong, geographically proximate relation between science and innovation.*

Especially, at the beginning of the life cycle (first and beginning the of second stage) scientific inputs are crucial for the development of a technology. Furthermore, biotechnology is expected to rely on academic research because it is more connected to already existing clusters (in line with [29]). Thus, we suggested that the bioeconomy patents of the field biotechnology also connect to research hotspots. The biomass subfield instead is assumed to have already reached the mature stage in its life cycle, so scientific inputs play a minor role. Therefore, we hypothesize:

*H4b: The amount of overall publication activity in a region is more linked to innovation activity in* *the biotech, and maybe also in the biomaterial subfields, than to other innovation activity but less to innovations in biomass.*

## 3 Methodological approach

### *3.1 Data*

To examine the factors influencing the location of German bioeconomy patents, we develop a data set with patents from various subfields of the bioeconomy including the location (municipality of inventors) and the priority year. Based on Frietsch et al. [41], we use three fields of the bioeconomy, namely biomass, biotech, and biomaterials. The identification of adequate keywords for these fields are based on all keywords which frequently (more than ten times) occurred in the patent database (PATSTAT database of the European Patent Office). Frietsch et al. [41] from Fraunhofer ISI and the European Commission determined IPC classes for the three fields of the bioeconomy. We calculated for all our keywords the precision and recall values for three fields according to their occurrence in patents assigned to the respective IPC classes. Then, we ranked the keywords according to the $F_{0,5}$-value, which is a combination of the two, laying more weight on precision than recall [42]. Next, we built subfields with high $F_{0,5}$ and precision value (usually above 15% with exceptions such as the term biomass, which is included because it has the name of a field). The subfields in Table 1 were then built qualitatively, researching the related terms, and categorizing them. We use the keywords assigned to each subfield to identify all patents and publications that contain at least one of the keywords in their title or abstract.

Table 1: Fields, subfields, respective keywords and the number of patents found.

| **field** | ***subfield*** | **respective keywords** | **patent count** |
|---|---|---|---|
| **Biomass** | *Biomass* | biomass | 522 patents between 1999 and 2019 |
| | *biomass-related* | biomass pyrolysis<br>biomass pellets<br>processing biomass<br>biomass drying<br>woody biomass<br>biomass feedstock<br>biomass carbon<br>biomass particles<br>biomass fuel<br>biomass waste<br>waste biomass<br>biomass materials<br>solid biomass<br>biomass fuels<br>biomass energy | 32 patents between 1999 and 2019 |

| | | | |
|---|---|---|---|
| | *wood-related* | wood tar<br>wood gas<br>woody biomass<br>forestry wastes<br>wood pellet<br>wood pellets<br>wood wastes | 16 patents between 1999 and 2019 |
| | *fuel* | refuse-derived<br>refuse derived fuel<br>refuse derived<br>refuse-derived fuel<br>biomass fuel<br>bio-oil<br>fuel production<br>fuel briquettes<br>biomass fuels | 17 patents between 1999 and 2019 |
| **Biotech** | *plant-related* | soybean plants<br>plant tissue<br>plant parts<br>maize plant<br>soybean variety<br>rooting | 243 patents between 1999 and 2019 |
| | *biopolymers* | explant<br>gene therapy<br>tissue culture<br>DNA recombination<br>transgenes<br>genetic material<br>transfection<br>transgenic<br>pseudomonas | 414 patents between 1999 and 2019 |
| | *genetics* | explant<br>gene therapy<br>tissue culture<br>DNA recombination<br>transgenes<br>genetic material<br>transfection<br>transgenic<br>pseudomonas | 1039 patents between 1999 and 2019 |
| **Biomaterials** | *natural rubber* | natural rubber | 131 patents between 1999 and 2019 |
| | *polysaccharides* | alkali cellulose<br>cellulose ethers<br>polysaccharides<br>hemicellulose<br>starches<br>heparin<br>cellulose esters | 230 patents between 1999 and 2019 |

| | | | |
|---|---|---|---|
| | *oil & oily plants* | free fatty acids<br>biodiesel<br>oil yield<br>fatty oils<br>oils and fats<br>soybean plants<br>vegetable oils<br>fats and oils<br>seed oil | 461 patents between 1999 and 2019 |

Before 1999, the number of bioeconomy patents is extremely low, and data on the additional variables is lacking. Additionally, the interest in the bioeconomy grew since the turn of the millennium. Therefore, we restrict the analysis to the years since 1999. Table 1 shows that the number of patents is rather low for three of the ten subfields. Due to the detailed view of the patent data, some of the subfields, like the wood-related subfield, contained too little data to be included in the regression analysis and were therefore excluded. Another reason for the exclusion is the idea to look carefully into the specific cases that result from the analysis, which needs a reduction to the most important subfields. Otherwise, the resulting data would have been too diverse and detailed. We conducted the analysis also for these subfields but used the results only as a control. The results without the extremely small subfields are rather insignificant, not at all conflicting. Overall, 3105 patents were captured. For the analysis itself, the subfields biomass-related, wood-related, and fuel were excluded, and therefore 3.040 patents remained and were included in the analysis.

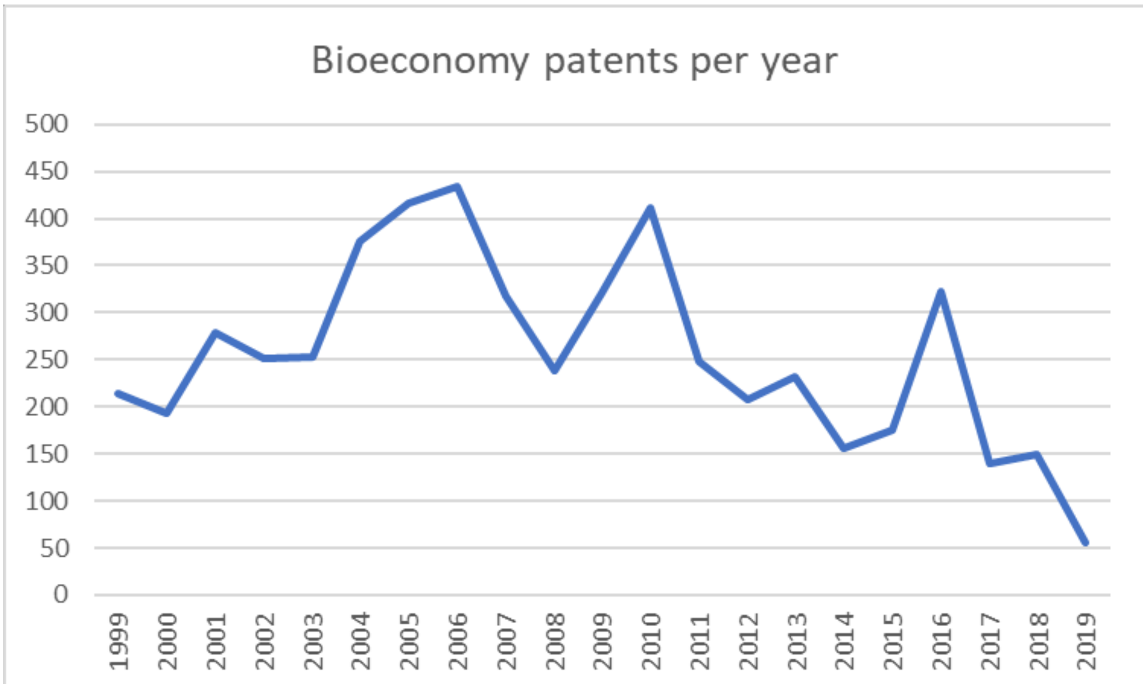

Figure 1: Bioeconomy patents per year as a result of the keyword approach.

Figure 1 displays the amount of bioeconomy patenting found with our analysis in the three fields. Contrary to the public perception of the bioeconomy topic, the amount of patenting is recently showing a decreasing trend. Data for 2018 and 2019 (and probably 2017) is not complete due to disclosure delays inherent to the patent process. One possible explanation for this trend could be that investment is not sufficient due to a lack of possibilities to make a profit in the bioeconomy. But it is also possible that, in Germany, bioeconomy research is too science-oriented and too much concerned with basic research. A third possibility is that the topics merge so much with the whole economy that we do not recognize them anymore as bioeconomy. This, however, is not likely since our novel approach using keywords is considered to be extremely flexible and inclusive. Another explanation attempt could be that the overall life cycle of parts of the bioeconomy we studied is already coming to its fourth phase, in which innovation and patenting lose importance. Last but not least, the current dominant patent topics could differ from the ones we researched for the paper at hand. We see for example an increase in biomass patents but a decrease in all other subfields within the data. This indicates that there is a strong focus on biomass research that is related to biomass as a traditional field but with new ways of using the produced materials. One example is the dandelion research, that not only studies the biotechnological components of the extracted natural rubber, but also the breeding of the plant itself [1].

### *3.2 Regression approach*

We apply a logit model to examine the location determinants of the bioeconomy patents in comparison to other randomly chosen patents. With this approach, we are independent of the development of the patenting activity over time. We investigate, which characteristics of a location increase the probability that a patent at a certain place and time falls into the category of bioeconomy compared to any other category. To obtain the necessary counter-factual cases, for each bioeconomy patent there are three other patents randomly selected from the same year and added to the data set with all relevant variables.

Our independent variables arise from our theoretical considerations above. They are all calculated at the municipality level. However, we do not assume that only the factors within a municipality are relevant but believe that the surrounding of the municipalities also matters. We deploy the methodology proposed and applied by Scholl, Brenner and Wendel [43] and calculate for all independent variables of each municipality a spatially weighted value, which represents the independent variable in the surrounding of the patent location.

First, we use three independent variables that contain geographical information: *density* is the population density (inhabitants per square kilometer), *forestry area* is the share of the total area (in 100 hectares) that contains forest, and *agriculture area* is the share of the total area (in 100 hectares) that is classified as used for agriculture. All data is from the statistical offices of Germany and its federal states. The agriculture and forestry data refer to the year 2015, the population density is calculated for each patent for the same year. All three variables capture different aspects of how rural or urban a municipality is.

The fourth variable contains subsidy data. The FoeKat database of the German government contains information on governmental subsidies, mainly from the ministry of education and research. It classifies all subsidies in different fields and among these we can find the field of bioeconomy. All subsidies classified in this field (per inhabitant) are used as a variable that represents policy support. This variable is calculated individually for each of our three fields. To match subsidies from the FoeKat database to our three fields, the corresponding support programs were researched and categorized into different categories: mainly biomass, mainly biotech, mainly biomaterials, and overarching topics. Usually, the different subsidy programs reveal their focus on one of the fields on their internet presence. Since the effects of subsidies may take time to evolve, we tested five different periods (actual year, last year, last two years, last three years, and last 5 years) and decided on the last period because it covers different time lags, provided the best regression fits, and fits the period in our other time-sensible variables, providing a consistent appearance (*FoeKat*).

As the fifth variable, we include the topic-specific patent activity (which results from the keywords of the subfields) per inhabitant in the years before the considered patent was filed (*topic.pat.last5*). By this, we check for the existence of path dependency. As periods, we tested the last 5 years as well as all prior patents to compare how long-lasting potential path dependency is. A better fit is obtained for the 5-year period.

The sixth variable is the total number of patent applications per inhabitant to check whether bioeconomy patents occur more frequently at highly innovative locations (*patents*).

Scientific research might influence the bioeconomy patent activity. Our seventh and eighth variables are built in analogy to the fifth and sixth but now referring to publication data. We include the number of total (*publications*) and topic-specific publications (data was obtained from the Web of Science). Again, for the topic-specific publication activity, two periods (5 years versus all prior publications) are tested leading to a better fit for the 5-year period, which is finally used (*topic.publ.last5*).

Since the bioeconomy support programs of the German federal government were launched in 2010, we further explored whether the results change if the data is divided into two periods. The first results show only few differences between the periods. Hence, the support programs may have increased bioeconomy patent activity but not changed the mechanisms of path dependence and the influence of local characteristics.

The following Table 2 gives an overview of the used independent variables:

Table 2: Overview of the independent variables

| **independent variable** | **content** |
|---|---|
| density | population density (inhabitants per square kilometer) |
| forestry area | forestry area in 100 hectares |
| agriculture area | agriculture area in 100 hectares |
| FoeKat | subsidy data from the German catalogue of all subsidies |
| topic.pat.last5 | patent activity with the specific topic of the dependent variable patent (past 5 years) |
| patents | total number of patent activities per inhabitant |
| topic.publ.last5 | number of topic-specific publications per inhabitant (past 5 years) |
| publications | total number of publications per inhabitant |

Our data shows several correlations between the variables with differences between the subfields. To check the influence of the correlation on our results, we excluded correlated variables successively and looked at how results changed. The estimated coefficients were robust and therefore, we decided to include all variables despite correlations.

## 4 Results and discussion

First of all, we find that population *density* is associated negatively with the occurrence of bioeconomy patents. This holds for many subfields and almost all cases, in which the coefficient is significant (exemption: biopolymers in the first period). It means that inventions within the field of bioeconomy tend to take place less in the metropolises and more in less populous places compared to the average patent activity. Hence, we can reject hypothesis 1a for the following subfields: plant-related, genetics, and oil & oily plants. These significant results are negative, showing that patents of these subfields occur more often in less populous areas. For the subfield biomass we can verify the hypothesis H1a. We assume that there is a strong connection of the whole bioeconomy to its mostly natural materials and their availability. The other possibility is that the bioeconomy innovation processes are quite distinct and occur away from the established centers. One example here is again the dandelion, where the research needs more space because of the plantations [1].

Further independent variables are associated with socio-geographical characteristics of a region are *agriculture area* and *forestry area*. These coefficients are significant for the whole field of biotech and the subfield natural rubber. They are positively significant for biopolymers and weakly positively significant for natural rubber. For plant-related, both are negatively significant only in the second period. It is surprising that the patents of the subfield biopolymers are more frequently in places with more agriculture and forestry area, while patents of the subfields plant-related and genetics are rather away from agriculture and forestry. Summing up, we do not find a clear structure for the dependence of bioeconomy patents on agriculture or forestry area. Hypothesis 1b can be rejected for biopolymers, while it must be verified for the subfield genetics. Most surprisingly, there is no significant relationship between the area of agriculture or forestry and patenting in the field of biomass. This also holds for most of the other subfields.

Table 3: Regression results within the field biomass.

| biomass | 1999 - 2009 | 2010 - 2019 |
|---|---|---|
| variable | biomass coef. | biomass coef. |
| _intercept | -0,269 | 2,754 |
| density | -0,002 | -0,003 * |
| forestry area | -1,259 | -3,170 |
| agriculture area | 0,280 | -4,576 |
| FoeKat | 1,096 (*) | 0,016 |
| topic.pat.last5 | 10,922 *** | 6,701 * |
| patents | -0,308 * | -0,567 *** |
| topic.publ.last5 | -5,361 | 5,329 |
| publications | -0,064 | 0,445 * |
| n | 918 | 1217 |

alpha: *** < 0.1% / ** < 1% / * < 5% / (*) <10%

Table 4: Regression results within the field biotechnology.

| biotech | 1999 - 2009 | | | 2010 - 2019 | | |
|---|---|---|---|---|---|---|
| variable | plant-related coef. | biopolymers coef. | genetics coef. | plant-related coef. | biopolymers coef. | genetics coef. |
| _intercept | -1,929 | -10,602 ** | 4,084 (*) | 18,958 * | -23,872 *** | 5,485 |
| density | 0,000 | 0,004 ** | -0,005 *** | -0,009 ** | 0,001 | -0,003 * |
| forestry area | 4,749 | 9,346 * | -4,532 (*) | -18,399 * | 19,899 *** | -5,006 |
| agriculture area | -0,575 | 10,374 * | -6,154 * | -23,588 * | 27,303 *** | -10,146 * |
| FoeKat | 0,039 | 0,037 | 0,027 (*) | 0,059 | -0,189 ** | -0,084 (*) |
| topic.pat.last5 | -2,402 | 2,185 (*) | 1,376 | 12,496 * | 22,698 *** | 1,162 |

| | | | | | | |
|---|---|---|---|---|---|---|
| patents | -1,128 *** | -0,433 ** | -0,687 *** | -1,350 *** | 0,597 ** | -1,440 *** |
| topic.publ.last5 | 28,895 *** | 0,487 | 30,671 *** | 1,316 | 0,837 | 16,187 * |
| publications | -0,071 | 0,306 *** | 0,070 | 0,899 (*) | 1,299 *** | 1,707 *** |
| n | 510 | 921 | 2759 | 308 | 553 | 1243 |

alpha: *** < 0.1% / ** < 1% / * < 5% / (*) <10%

The next interesting findings are the coefficients of the variable *FoeKat*. Since the German Federal Government explicitly established a subsidy program for the bioeconomy and promotes Germany as one of the main innovators within the bioeconomy, we expected to determine a high number of bioeconomy-related patents especially within the second period after publishing the National Research Strategy Bioeconomy 2030. For the subfield plant-related it is insignificant (in both periods). The data does not support an impact of public funding on the patenting probability for this subfield. However, *FoeKat* changes from insignificant to positively significant in the subfields natural rubber and oil & oily plants, whereas for biomass and polysaccharides, it changes from positive to insignificant. Hence, we find positive impacts of government subsidies on the patent activities in some subfields, although not in all of them. However, the lack of significance might be caused by the low number of patents or the inability of the approach to detect smaller effects. Overall, not as clear as expected but the data rather supports hypothesis 2, at least in one of the periods.

A significant negative relationship was found for biopolymers and genetics: The coefficient for *FoeKat* is positively significant or insignificant in the first period and becomes negatively significant in the second period. This means the subsidies reduce the likelihood of the emergence of a patent with the keywords subsumed under the subfields biopolymers and genetics. The development from a non-existing relationship to a highly significant positive correlation with publications also need to be highlighted for genetics. These two results combined are in line with the findings of Hüsing et al. [44] that German companies do not fully exploit the available subsidies. One explanation for the negative relationship of subsidies with genetics patents might be that the focus of subsidies has moved from the support of firms to support of science in a broader sense. It might be the case that scientific and technological developments have broadened the field of genetics. This would also explain the decrease in path dependence and the relationship with topic-specific scientific activity. Support of a narrower bioeconomy might be rather diametral to such new developments. It needs to be emphasized, that this logit regression does not show causal relations.

Table 5: Regression results within the field biomaterials.

| biomaterials | 1999 - 2009 | | | 2010 - 2019 | | |
|---|---|---|---|---|---|---|
| variable | natural rubber coef. | oil & oily plants coef. | polysaccharides coef. | natural rubber coef. | oil & oily plants coef. | polysaccharides coef. |
| _intercept | -10,534 | 8,855 | -3,909 | -17,230 | 9,778 | -3,278 |
| density | 0,001 | -0,004 * | -0,001 | 0,001 | -0,006 (*) | -0,002 |
| forestry area | 11,630 | -10,063 | 3,302 | 23,093 (*) | -11,276 | 1,004 |
| agriculture area | 12,001 | -11,611 | 5,227 | 17,891 | -12,880 | 3,940 |
| FoeKat | -0,278 | 0,119 | 0,364 * | 0,720 * | 0,594 ** | 0,136 |
| topic.pat.last5 | 12,677 *** | 10,023 *** | 6,418 ** | 9,040 ** | 17,225 *** | 11,006 ** |
| patents | -0,874 ** | -0,231 | -0,575 *** | -0,902 * | -0,561 | -0,977 *** |
| topic.publ.last5 | 3,992 | 0,324 | 3,376 | 16,741 *** | -2,376 | 12,072 |
| publications | 0,176 | 0,081 | -0,117 | -1,025 (*) | 0,240 | 0,394 |
| n | 296 | 562 | 1089 | 210 | 271 | 728 |

alpha: *** < 0.1% / ** < 1% / * < 5% / (*) <10%

Regarding the last four independent variables, we can generally see relatively consistent negative results for the overall patent activity (*patents*), which confirms hypothesis 3b. The only exemption are patents in the second period in the biopolymers subfield. There is a shift in this subfield so that innovations become more likely to emerge proximate to a high overall patent activity, i.e., innovative hotspots. This might signal that the subfield of biopolymers has entered a phase with new developments that build on various technologies, probably broadening the scope of use, which is indicative of the second ILC stage. Besides the case of biopolymers, we find that in five of the seven subfields the overall patent activity is negatively associated with the occurrence of our bioeconomy patents in both periods. This means that patents in the bioeconomy are generally not connected to the overall patent activity.

While the literature discusses that new technological developments are often based on already existing related technologies, which causes also spatial proximity, this seems to not be the case for most of the bioeconomy. Technological developments in the bioeconomy seem to be rather radical and independent from the usual innovation activity. This is supported by the fact that many actors are new firms. We might see changes in this when the bioeconomy evolves further and interacts more with the rest of the economy. The biopolymers might be the first subfield of the ones studied here, where this integration can be seen with an increased relationship with other innovation activities.

Furthermore, we determined that the total publication activity (*publications*) at a place has no significant coefficients in all three biomaterial subfields. The only exemption is one weakly negatively significant relationship for natural rubber in the second period. However, biomass and biotech patents are associated with a higher overall publication activity in the second period, which supports hypothesis 4b only in the case of biotech. For the subfield biomass hypothesis 4b has to be rejected, because the data shows a positively significant relationship. In biopolymers, the relationship between innovation and the overall publication activity is significant already in the first period but the coefficient increases, i.e., the relation between biopolymer patents and the total publication activity becomes stronger over time. Hence, we observe for biomass and biotech an increasing positive relationship between the location of patent activity in these fields and the general scientific activity. This might indicate a broadening of these fields, probably caused by a spread of the use of these technologies in many economic and technological activities.

Now let us take a look at prior local bioeconomy publications and patents (*topic.pat.last5* and *topic.publ.last5*) i.e. path dependence. Patenting activity in the same thematic topic in the past is related to higher probability of a new patent in the same subfield, at least in any subfield in the second period. The only exemption here is genetics with an insignificant result. The respective coefficients are in most cases positive and significant, which verifies hypothesis 3a: We expected former innovation activity in the bioeconomy to be positively linked to recent bioeconomy innovation. Hence, we can determine a strong path dependence. This adverts to the suggestion that the bioeconomy patenting within the researched subfields has reached at least the second stage of their life cycle. In several subfields, namely plant-related, biopolymers, oil & oily plants, and polysaccharides the relationship with previous patents in the same subfield has increased from the first to the second period, which indicates that these fields have reached or are in the second stage during the examined period.

The results for publications on the same topic are less straightforward, i.e. hypothesis 4a gets only weak support from the data. There is no relationship between biomass, biopolymers, oil & oily plants, and polysaccharides in any of the periods. In one biotech subfield (plant-related), an initially positive relationship becomes insignificant after 2010. This is in line with the life cycle theory, according to which scientific results are important at the beginning, while with the development into the second and third stage process innovations become the dominant innovation activity. Thus, this also confirms that most of the studied subfields are already in the second stage or entered this stage during the observed period.

In one biomaterials subfield, namely natural rubber, an insignificant relationship becomes positively significant in the second period for topic-specific publications. This does not fit the stylized life cycle theory because it means that scientific inputs become increasingly relevant again. A plausible explanation is that in these subfields new developments have occurred in the second period. These new developments may have their origin in new scientific findings, causing an increase in the connection between science and economy. The development of the subfield plant-related in contrast shows similarities to the stylized ILC since it has a positively significant relationship to topic-specific publications that becomes insignificant in the second period. This could indicate the entry into the second ILC stage. In genetics, the relationship stays positively significant in both periods, hinting at a constant importance on scientific findings.

We strongly based our theoretical assumptions on the industry and technological life cycle model. Hence, we can use these results to discuss the applicability of this theory. Most of the results imply that the examined subfields are either in the second ILC stage or have reached this stage during the study period. Hence, in general, we find a good fit with the ILC model. However, two findings are not in line with this theory. First, for natural rubber, the topic-specific publications only show a positive significant result in the second period. During the life cycle, the relevance of scientific results should decrease. Our results indicate that there are subfields in the bioeconomy that have recently seen new developments (such as the use of dandelions) that change the usual life cycle development. Second, in the case of biopolymers, we find an increasing localization of patents in places that are characterized by high overall patent activity. The life cycle model predicts this rather at the beginning when high overall innovativeness makes the new developments more likely. The bioeconomy seems to be different, emerging rather not in the innovation hotspots but moving there, when it becomes more integrated into the overall economy.

## 5 Conclusions

By applying a logit regression model to a rich database at the municipality level, we analyze seven subfields of the bioeconomy, subordinated to the three fields of biomass, biotechnology, and biomaterials. The subfields were built with a keyword-driven approach and are named as follows: biomass, plant-related, biopolymers, genetics, natural rubber, oil & oily plants, and polysaccharides. Certain combinations of several keywords represent the basis for these subfields. The paper at hand contributes to the challenge of researching localization determinants of the bioeconomy at the municipality level [3]. The bioeconomy is seen as one of the possibilities to meet the depletability of resources and to make the future economy more sustainable and less dependent on fossil-based resources [6]. Therefore, it is important to understand which determinants influence the occurrence of bioeconomy patents in Germany. The following conclusion gives possible answers to this question and also to the posed hypotheses within this paper.

Our results show that patents related to the seven researched subfields are more frequently located in areas with lower population density than other patents. While many new developments occur rather in big cities, this does not seem to be the case for the bioeconomy. Not only the field biomass is located within areas with lower population density but also all other fields studied here, except the biopolymers subfield. The results on the connection with the area of forestry and agriculture are mixed, most surprisingly there is no relation to the field of biomass.

We expected a positive influence of the public subsidies depicted through the variable *FoeKat* for the occurrence of bioeconomy patents. For the subfields of biopolymers and genetics, we find a negative relationship, which might be caused by specific developments in these fields and the focus of the government [6]. In contrast, for two of the three subfields of biomaterials, and weakly for the subfield of biomass, the federal government's subsidies increase the likelihood of the creation of bioeconomy patents. Hence, the overall effect of governmental funding is not as straightforward as expected but nevertheless positive.

Concerning the influence of the overall patent activity on the occurrence of bioeconomy patents, we anticipated a negative relationship. The data show significantly negative results in all subfields except in the subfield of biopolymers. It can be assumed that the patenting process of nearly all subfields is independent, and hence less likely occurring at the same locations compared to the overall patent activity. In connection with this, path dependence for topic-specific patents can be detected in all fields, respectively all subfields. Consequently, we can conclude that former bioeconomy patents lead to a higher chance of new bioeconomy patents within the same topic and location. This fits the discussion within the literature [29, 36–38] and strengthens the suggestion, that the researched bioeconomy is at least in the second stage of the ILC [21].

The last hypothesis relates to the topic-specific and overall publication activity, assuming that both variables lead to enhanced bioeconomy innovation. In this regard, the analysis shows mixed results. It can be assumed that the relation of patenting within the bioeconomy and publications at a location slightly changed from a topic-specific emphasis to a broader (scientific) basis. This indicates that the bioeconomy reached a stage in which the crossover character of the bioeconomy becomes more decisive for the innovation activity.

Certainly, there is room for further research to give a deeper insight into the dynamics of the German bioeconomy. Investigation is needed to find out why the overall patent numbers are decreasing and if there is a change within the focus of the public subsidies. Beyond that, it would be interesting to (qualitatively) research where and by whom the public subsidies are accessed. Furthermore, this present analysis would also be interesting for other parts of the bioeconomy to obtain a broader perspective on the different life cycle stages and the development of the bioeconomy as whole. Consequently, we argue that besides considering the existing global and national bioeconomy agendas and strategies, it is of utmost importance to integrate municipalities as a research scale to enhance present understandings of the development of the bioeconomy. This study on the one hand depicts a geographical point of view and on the other hand provides useful insights for diverse stakeholder groups such as politicians, scientists, or private and public sponsors. One key aspect of understanding the development of the bioeconomy is to analyze its localization determinants on small scales – that's where the dandelion meets the road!

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