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Papers in Evolutionary Economic Geography

23.13

https://www.tandfonline.com/doi/full/10.1080/09654313.2024.2308027

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Acknowledgements

The authors are very grateful to Ingo Liefner for his contribution to the development of the research question as well as to Anne Otto and Lars Mewes for the stimulating exchange on the potentials of sequence analytical methods for empirical research in economic geography. Moreover, the authors would like to thank Sandra Gottschalk and Johannes Bersch for the access to and help with ZEW's company database. This study also benefited greatly from the numerous comments at the RSA Winter Conference in London (November 2022) and at a research seminar at GSSI in L'Aquila (February 2023).

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Abstract

Given that eco-innovations and the associated renewal of economic structures are pivotal in addressing environmental problems, economic geography research is increasingly focusing on their spatio-temporal dynamics. While green technological and industrial path developments in specific regions have received considerable attention, little effort has been made to derive general patterns of environmental inventive activities across regions. Drawing on unique data capturing both green incumbent and green start-up activities in the 401 German NUTS-3 regions over the period 1997-2018, this article aims to trace and compare the long-term green regional development. For this purpose, we introduce social sequence analysis methods to economic geography that allow us to understand the constitution of regional eco-innovation trajectories. The findings suggest that regions mainly display distinct trajectories. Yet, structural similarities emerge in the sense that regions of the same type occur in spatial proximity to each other and show persistent specialization patterns. These range from the simultaneous presence or absence of green incumbents and green start-ups to the dominance of just one of the two groups of actors. Only some regions manage to establish an above-average eco-innovation specialization over time. Since this greening originates from either green incumbent or green start-up specialization, green regional trajectories can be assumed to unfold mainly in a path dependent and less radical manner. In summary, this study provides important empirical and methodological impulses for further in-depth analyses to disentangle spatio-temporal phenomena in economic geography.

Key words

eco-innovation, green regional development, path dependency,

regional transitions, social sequence analysis

1. Introduction

Among the main interests of evolutionary approaches in economic geography has been the exploration of regional innovation and industry dynamics. There is consensus that both established and new regional trajectories build to a large extent on local preconditions, particularly emphasizing historically grown technological capabilities, support structures, and knowledge bases. As such, the spatial unevenness of economic activities is mainly seen to result from path and place dependent processes (Boschma and Frenken 2006; Martin and Sunley 2006; Boschma and Frenken 2011; Pike et al. 2016; Henning 2018). More recently, evolutionary studies have also devoted specific attention to the development of green industries and green technologies, as these hold the promise of both creating economic benefits and reducing environmental burdens (Tanner 2016; MacKinnon et al. 2019; Njøs et al. 2020; Gibbs and Jensen 2022; Eadson and van Veelen 2023).

In general, green path development comprises the restructuring of existing industries and path creation through the emergence of new green industries. Fundamental to both phenomena is the development and application of green services, products, and processes, which are usually considered as green or eco-innovations (Cooke 2012; Grillitsch and Hansen 2019; Tödtling, Trippl, and Frangenheim 2020; Trippl et al. 2020). While it is well established that technological relatedness crucially influences green industry emergence (Tanner 2016; Santoalha and Boschma 2021), much progress has also been made in considering its wider enabling and constraining context factors. These include, in particular, agency and actor constellations as well as the influence of organizational and institutional configurations (Dawley 2014; Binz, Truffer, and Coenen 2016; Steen and Hansen 2018; MacKinnon et al. 2019; Sotarauta et al. 2021). This broader understanding of green regional development has also increasingly resulted in studies complementing evolutionary with systemic perspectives, such as technological or regional innovation system approaches (Grillitsch and Hansen 2019; Njøs et al. 2020; Tödtling, Trippl, and Frangenheim 2020; Trippl et al. 2020).

However, despite recent attempts to look more broadly at green regional development patterns, research has so far been mostly informed by regional case studies focusing either on specific green industries (Binz, Truffer, and Coenen 2016; Tanner 2016; Steen and Hansen 2018; Gibbs and Jensen 2022) or green technologies (Njøs et al. 2020; Jakobsen et al. 2022). It therefore remains largely unclear if and to what extent the identified industrial and technological specificities affect broader green path development processes of regions. Similarly, proposed regional typologies of green industrial development require empirical validation, as they are largely based on the results of case-specific analyses and conceptual arguments (Grillitsch and Hansen 2019; Tödtling, Trippl, and Frangenheim 2020). Furthermore, little attention has been paid to comprehensive regional comparisons over a longer period of time. Although the persistence of green path development processes is often emphasized, albeit implicitly, scholarly debates suffer from lacking insights on regions' long-term stability and change in green innovative activities beyond individual industries or technologies.

To address these research gaps and shortcomings, the present article is inspired by Trippl et al.'s (2020) research on green economic restructuring and asks how eco-innovation development unfolds across different regional contexts. In doing so, this work differs from previous research in several aspects. First, we use unique green patent and green start-up data to ensure a broad perspective on innovation activities and to distinguish the relative importance of incumbents and newcomers using specialization measures. Second, our contribution traces eco-innovation specialization for the 401 German NUTS-3 regions over a period of 1997-2018, which ensures spatial granularity and a long-term perspective. Third, we advance economic geography's methodological portfolio by introducing and applying social sequence analysis methods. These are particularly suitable for capturing both unique regional development patterns and the similarity between regional trajectories. On the basis of the latter, we derive, characterize, and compare different types of regional pathways. As such, this empirical approach provides advanced empirical insights on region-specific patterns of green innovation activities and gives indications of how green regional trajectories evolve over time.

The remainder of this article is structured as follows. The next section summarizes the literature on regions' green industrial and green technological path development. This is followed by the methodological section that describes green patent and green start-up data, related eco-innovation specializations measures, and social sequence analysis. The results section highlights differences, similarities, and characteristics of regional eco-innovation trajectories. The main findings are then critically discussed, before the final section concludes and sheds light on promising implications for future research.

2. Theoretical background

As a central pillar of economic geography research, burgeoning evolutionary approaches have for some years been concerned with historical processes leading to an unevenness of economic activities across space (Martin and Sunley 2006; Boschma and Frenken 2006; Essletzbichler and Rigby 2007; Boschma and Frenken 2011; Dawley 2014). Originating from evolutionary economics and its core hypothesis of the inheritance of organizational routines (see Nelson and Winter 1982), evolutionary economic geography (EEG) emphasizes the place-specificity of innovation, industrial, and economic processes. Conceptually, the research mainly relates to regional path development, including new path creation, and regional branching approaches. As confirmed by a multitude of EEG studies, spatial development strongly depends on locally available related technologies and competencies, as well as cumulative dynamics of knowledge generation and diffusion in and across territories (e.g. Tanner 2014; Heimeriks and Boschma 2014; Pike et al. 2016; Neffke et al. 2018; Martin, Martin, and Zukauskaite 2019). Complementary institutional, actor-specific and political interdependencies ultimately lead to persistent path and place dependent processes associated with gradual changes (Binz, Truffer, and Coenen 2016; MacKinnon et al. 2019; Grillitsch and Sotarauta 2019; Jakobsen et al. 2022). Substantial progress has recently also been made regarding the consideration of green spatial development, with the core focus touching on the question of how change towards sustainability unfolds in regions, knowing that their development is highly path dependent.

2.1 Green regional development

The literature on green path development incorporates key ideas of EEG regarding the development of regions, but pays particular attention to the structural preconditions and opportunities that affect the greening of regions. Usually, green path development is understood as the development and emergence of those industries that contribute to the reduction of environmental impacts (Capasso et al. 2019; Grillitsch and Hansen 2019; Njøs et al. 2020). In addition to the latter, green industrial development is also expected to create positive economic impacts. As such, the focus is usually on the generation and diffusion of new products and technologies, i.e. eco-innovations, as well as the role of multiple and diverse actors and agency in shaping institutional frameworks that crucially influence green path development (Sotarauta et al. 2021; Gibbs and Jensen 2022; Eadson and van Veelen 2023). In that regard, Trippl et al. (2020) make a more general distinction of green regional path development processes between the emergence of new green growth pathways and the greening of existing industries.

To explain where and how green industrial activities emerge across space, studies mostly look at regionally evolved structures. These set the framework conditions that are seen as either enabling or hindering green path developments at the regional level. On the one hand, it is therefore fundamentally a matter of transforming promising opportunities and potentials in such a way that green path development processes are induced. On the other hand, however, it is also about how possible barriers due to unfavorable regional structural conditions can be overcome (Capasso et al. 2019; Trippl et al. 2020). Against this background, studies increasingly refer to extra-regional factors, especially since region-specific preconditions of knowledge and other resources for green industrial development are often sparsely developed (Binz, Truffer, and Coenen 2016; Grillitsch and Hansen 2019).

In line with EEG's core hypothesis, green industrial developments are more likely to unfold in those regions where the necessary knowledge base is available. More precisely, particular reference is made to the importance of technological and sectoral relatedness and cumulative knowledge production (Tanner 2016; Calignano, Fitjar, and Hjertvikrem 2019; Santoalha and Boschma 2021). Conversely, poorly developed structures pose barriers. These include a lock-in of assets in old, unsustainable economic activities as well as institutional and political inertia. As a consequence, changing framework conditions are no longer sufficiently taken into account, i.e. the need to address environmental challenges, which results in negative path dependencies that are accompanied by a loss of capabilities (Steen and Hansen 2018; Tödtling, Trippl, and Frangenheim 2020; Trippl et al. 2020). These developments are often, though not necessarily, reinforced by incumbent behavior, characterized by strong vested interest, as structures were already shaped accordingly in earlier regional path development processes (Steen and Hansen 2018; MacKinnon et al. 2019; Baumgartinger-Seiringer 2022).

Whether the modification of the regional asset base necessary for green path development will succeed is an open question due to the strong competition for resources; not only between old and new industries (Tödtling, Trippl, and Frangenheim 2020), but also between several new (green) technology pathways emerging in regions (Jakobsen et al. 2022). Given the complexity of green regional development, it is therefore surprising that studies have so far focused almost exclusively on individual industries in specific regions. Consequently, a generalization of green path developments at the regional level is needed to capture spatial differences in their entirety. Without neglecting industrial and technological specificities in different regions, the identification of different types of regions is an important step that helps to assess general development patterns and to better understand greening activities beyond idiosyncratic cases.

2.2 Types of green regional development

Within economic geography and related disciplines, a systemic understanding of innovation complements evolutionary approaches. The regional innovation systems (RIS) approach has been particularly influential for more than three decades now, focusing on interactions of agents from the public and private sectors, which significantly influence innovation activities within and between regions. In essence, internal organizational capacities are complemented by the external environment, so that the political, socio-cultural and institutional framework conditions stimulate entrepreneurial activities, learning and knowledge processes as well as innovation. These phenomena are particularly influenced by geographical proximity, which explains the rationale of a RIS perspective. Moreover, regions often have own governance capacities, allowing them to exert immediate influence on innovation activities (Cooke 1992; Asheim, Smith, and Oughton 2011; Isaksen and Trippl 2016; Asheim, Grillitsch, and Trippl 2016).

In the context of green regional path development, the RIS approach is often used to understand which actors as well as network and institutional structures influence innovative change towards environmental sustainability. The systemic perspective thus contributes to a better understanding of the sources and patterns of the geography of eco-innovations and green path developments (Tödtling, Trippl, and Frangenheim 2020; Trippl et al. 2020). As regions face specific failures and challenges due to their structural preconditions, Grillitsch and Hansen (2019) propose a typology of different green development pathways. The authors pay special attention to the directionality of policy measures[1] that are necessary for the greening of regional economies. Overall, they claim that green industrial development differs between peripheral (1), green specialized (2), dirty specialized (3), as well as metropolitan regions (4). Although the delineation of different types of regions is not unambiguous, which explains the variety of existing regional typologies (see, e.g., Asheim, Grillitsch, and Trippl 2016), it allows a regional characterization in a stylized manner.

Peripheral regions (1) often lack a critical mass of actors and distinct network structures as well as industrial activities (Dawley 2014; Grillitsch and Hansen 2019). As a result, barriers exist in promoting and expanding green economic activities and industries. In this context, Tödtling et al. (2020) refer to the start-up challenge that often results from both an insufficient knowledge base and a lack of financial and organizational support measures. Opportunities for

[1] Recent work has also taken up aspects of directionality and normativity to further develop the RIS approach. See, for example, Tödtling et al.'s (2022) notion of “challenge-oriented RISs” (CoRISs).

green path development therefore are seen in influencing regional conditions in such a way that they facilitate the implementation of environmentally friendly technologies. In addition, the few central actors need to be strengthened and aligned so that potential green niches are formed, always striving to attract external knowledge (Dawley 2014; Grillitsch and Hansen 2019; Calignano, Fitjar, and Hjertvikrem 2019). Yet, the role and opportunities of peripheral regions in greening the economy remain largely vague, as the research focus is usually on leading regions.

In contrast, regions with a specialization in a green industry (2) usually have favorable conditions and promising opportunities to drive green advancements in the future. This is due to the pronounced levels of human capital endowment as well as infrastructural settings. Spin-offs, network structures and the development of the supplier industry are found to facilitate further green development (Grillitsch and Hansen 2019). While very few regions are able to establish dominance across several green technologies constituting various industries, those regions seem to be able to maintain it over longer periods of time (Barbieri et al. 2023). The resulting spatial persistence once again evidences the path dependency hypothesis put forward in the EEG literature (e.g., Tanner 2016; Perruchas, Consoli, and Barbieri 2020; Santoalha and Boschma 2021). However, the challenge for regions specialized in green industries is to avoid constraints due to negative lock-ins in the dominating industry (Asheim, Grillitsch, and Trippl 2016; Trippl et al. 2020), with the policy aim of developing new pathways and market opportunities beyond existing specializations (Grillitsch and Hansen 2019).

On the other hand, some regions have specialized in dirty industries (3), for example coal and oil regions. This type of region is particularly characterized by competition between established industrial paths and emerging green activities. As with green-specialized regions, there is the challenge of potential lock-ins manifesting in institutional and innovation systems rigidity, which hamper asset modification and environmentally friendly alternative pathways

(Grillitsch and Hansen 2019; Tödtling, Trippl, and Frangenheim 2020). As these regions typically face major restructuring, established actors, i.e. incumbents, are often the central actors (Steen and Hansen 2018; Calignano, Fitjar, and Hjertvikrem 2019). However, incumbents are characterized by pluralistic behavior, ranging from lobbying and maintaining the status quo to green niche activities (Baumgartinger-Seiringer 2022). The latter, in turn, seems more likely when green activities build on existing but related capabilities from dirty industries (van den Berge, Weterings, and Alkemade 2019; Santoalha and Boschma 2021). At the same time, another policy objective is to green dirty industries by applying new technologies from outside the region (Grillitsch and Hansen 2019).

Metropolitan regions (4) offer RIS conditions that generally have a positive impact on the development of green pathways. These include a broad knowledge and industrial base and a critical mass of diverse groups of actors. In principle, these preconditions facilitate green entrepreneurial activities through start-ups, as well as greening of existing actors (Trippl et al. 2020; Sotarauta et al. 2021). At the same time, there is a risk of fragmentation due to multiple innovation systems organizations', including those from unsustainable industries, competing for skills and capabilities (Asheim, Grillitsch, and Trippl 2016). Tödtling et al. (2020) frame this as the competition challenge usually found in metropolitan areas. The multiplicity and heterogeneity of actors thus calls for an innovation policy mix that aims at stimulating interaction and collaboration between and among diverse interest groups that ultimately induce the growing of green industries and the transformation of dirty activities (Grillitsch and Hansen 2019).

In summary, regional typologies of green path development often reflect ideal-typical patterns that emerge from the findings of specific case studies following inductive research approaches. However, it remains unclear to what extent the proposed types can be identified by means of a comparative research design. Our approach addresses this research gap by uncovering eco-innovation trajectories of regions in a quantitative-explorative way, on the basis of which we deductively derive distinct patterns and compare them with existing typologies. To do justice to the core ideas of EEG, we additionally take a long-term perspective that helps to better uncover persistence in green activities at the regional level.

3. Data and methods

As one of the first empirical studies in economic geography, we make use of sequence analytical methods. These approaches allow us to understand long-term regional pathways and to identify similar eco-innovation trajectories across regions. The methodological advancements are complemented by a unique combination of patent and company data for Germany. As such, we are able to go beyond patents' immanent technological focus and obtain a comprehensive picture of green innovation activities of both incumbents and start-ups.

3.1 Green patent and start-up data

Due to the lack of data on novel products, processes, and activities, the empirical literature captures (green) innovation through indirect measures. For regional comparative analyses, these usually range from survey and company data to patent-related measures (e.g., Corradini 2019; Giudici, Guerini, and Rossi-Lamastra 2019; Barbieri et al. 2023). To reduce proxy variables' limitations in terms of scope and accuracy, we combine information on green firm and green patenting activities, aggregated at the level of the 401 NUTS-3 regions in Germany. While patent data can be used to detect the greening of incumbents, i.e. green technology developments, firm demographics allow the identification of green start-ups (Doblinger, Surana, and Anadon 2019; Perruchas, Consoli, and Barbieri 2020).

In this study, patent information was retrieved from OECD's REGPAT database. It derives the PATSTAT database provided by the European Patent Office (EPO) and regionalizes all patent applications filed to the EPO as well as those filed under the Patent Co-operation Treaty

(PCT) at international phase since 1977 (OECD, REGPAT database, August 2022). Using the inventors' addresses, we assign patent applications to each German region involved. As such, we follow other studies and use non-fractional patent counts, where knowledge generation is understood as non-divisible (e.g. Tanner 2016; van den Berge, Weterings, and Alkemade 2019). The choice of NUTS-3 regions is a result of both data availability and the ambition of analyzing green path developments on the smallest-possible scale. While the REGPAT database allows direct regional assignment, the ENV-TECH classification (Haščič and Migotto 2015) helps to identify green inventive activities via the provided IPC/CPC codes. The ENV-TECH classification distinguishes a total of 95 technologies, ranging from environmental management to climate change mitigation in individual sectors, and is commonly used in the geography of eco-innovation literature (e.g. Santoalha and Boschma 2021; Losacker 2022; Barbieri et al. 2023).

Patent data is, however, not suitable for assessing green innovation activities of newcomers, i.e. start-ups. Besides the already low share of patent applications that are attributable to small and medium-sized enterprises (Eurostat 2014), many start-ups develop non-patentable business models. In fact, only about one in five start-ups in Germany is active in the development and production of technologies (Kollmann et al. 2022). To identify company foundations that can be considered green, we, therefore, rely on the Mannheim Enterprise Panel (MUP) of the Centre for European Economic Research (ZEW). As one of the most comprehensive databases, the MUP contains almost the entire stock of German companies by combining information from official registers, reports, websites, and enquiries (Bersch et al. 2014). Of particular importance for this study are the companies' addresses, year of foundation, economic sector, and activity descriptions. These allow us to make regional and temporal assignments, as well as to exclude less-innovative sectors in a narrower sense. The latter include company activities in the hospitality industry, public administration, education, health, and social services as well as arts, entertainment, and recreation. Using the activity descriptions, i.e. brief details of the entrepreneurial focus, we are ultimately able to identify green start-ups by means of a keyword-based search. For this purpose, we have identified environmentally-friendly technologies and applications for all sectors - energy, transport, buildings, waste management, etc. - as well as terms associated with climate and environmental protection (see Table A1 in appendix for details on the search strategy).

In principle, the MUP data comprise a detailed determination of business activities in Germany since the beginning of the 1990s. However, the years immediately after German reunification are biased, as company information from the territory of the former GDR were transferred to the then official business registers. Similarly, data of the most recent years is less reliable, as it takes some time for newly founded companies to appear in the official announcements (Bersch et al. 2014). This is comparable to patent data, where there is also a time lag between application and publication.

Since firms are usually still considered start-ups a few years after their foundation and the (green) knowledge output via patents also lasts for a certain time (Doblinger, Surana, and Anadon 2019; Cojoianu et al. 2020; Santoalha and Boschma 2021), we add the number of start-ups and patents of the previous two years to that of the corresponding year. Consequently, 1997 as year t_0 includes the start-up and patent counts since 1995. These moving windows acknowledge the cumulative nature of knowledge generation and innovative change. For the 22-year period between 1997 and 2018, we identify a total of about 115,200 green patents, while the number of green start-ups amounts to 86,100.

3.2 Green incumbent and start-up specializations in regions

After determining the number of green and non-green patents and start-ups per region and year, we aim to reveal the regions' comparative advantage in these different eco-innovation activities over time. The relative importance of both green incumbents and green start-ups helps to trace green regional trajectories beyond total innovation activities. To this end, we follow previous research on the geography of eco-innovation (e.g. Horbach, Chen, and Vögele 2014; Losacker and Liefner 2020; Perruchas, Consoli, and Barbieri 2020) and calculate the Relative Patent Advantage (RPA) and Relative Start-up Advantage (RSA) for each year and region. These measures indicate how the share of green incumbents and green start-ups in regions relates to the respective national average. In our case, RPA and RSA are normalized between -100 and 100, with positive values reflecting above-average green specializations of regions. We calculate:

$$RPA_{rgt} = 100 \times \tanh \ln \left[\frac{Patents_{rgt} / \sum_r Patents_{rgt}}{Patents_{rt} / \sum_r Patents_{rt}} \right] \tag{1a}$$

$$RSA_{rgt} = 100 \times \tanh \ln \left[\frac{Start\text{-}ups_{rgt} / \sum_r Start\text{-}ups_{rgt}}{Start\text{-}ups_{rt} / \sum_r Start\text{-}ups_{rt}} \right] \tag{1b}$$

where g relates to the number of green patents or green start-ups in region r and year t.

Against the background of the regional specialization with eco-innovation actors, we derive four different types of regions (see Table 1). Accordingly, green specialized regions are those that are specialized in both types of actors. In contrast, green start-up and green incumbent specialized regions are characterized by an above-average specialization in either of the respective two dimensions, while non-specialized regions show a below-average specialization in green incumbents and start-ups. To trace green regional development over time, we supplement the rather static character of this regional typology with a dynamic perspective.

Table 1: Dimensions of regional eco-innovation specialization

	Specialized in green start-ups (RSA > 0)	**Non-specialized in green start-ups (RSA < 0)**
Specialized in green incumbents (RPA > 0)	Green specialized	Green incumbent specialized
Non-specialized in green incumbents (RPA < 0)	Green start-up specialized	Non-specialized

3.3 Social Sequence Analysis

From an evolutionary perspective, it seems very promising to analyze how eco-innovation activities of regions have developed over longer periods of time. Are green regional pathways rather stable or do transitional patterns emerge? Which of the four dimensions of specialization dominates? To what extent do regional developments resemble each other?

A diverse set of methods that lend themselves precisely to this research interests are sequence analyses. First used in biology to compare and analyze DNA strands, sequence analysis methods have been introduced to and applied in social sciences since the mid-1980s, where they primarily help to determine trajectories of individuals such as life and career paths (Abbott 1995; Brzinsky-Fay and Kohler 2010; Gauthier, Bühlmann, and Blanchard 2014). Although the set of sequence analytical approaches can be applied to all temporal phenomena where individual units can be distinguished, these methods have hardly been used in geographical research domains so far. Exceptions comprise, for example, recent studies on population development, socio-economic inequalities and entrepreneurial ecosystems (Kuebart 2022; Patias, Rowe, and Arribas-Bel 2022; González-Leonardo, Newsham, and Rowe 2023). We therefore see enormous untapped potential for economic geography in which the development of spatial units over time is often put center stage.

In essence, social sequence analysis is applied to time series data, i.e. sequences, instead of individual data points. These one or multi-dimensional ordered arrays consist of a finite and non-ambiguous number of states (Abbott and Tsay 2000; Gauthier, Bühlmann, and Blanchard 2014). An individual sequence can thus be defined as "the succession of the observed states for one unit of observation over a given time period" (Gauthier, Bühlmann, and Blanchard 2014, 5). On a more abstract level, a sequence x of length l can be expressed by:

$$x = (x_1, x_2, \dots, x_l), \qquad with\ x_j \in A \tag{2}$$

where A denotes the finite set of states (Gabadinho et al. 2011).

With regard to our empirical analysis, each of the 401 regions represents a sequence with the states as the annual classification into the proposed four specialization dimensions, i.e. specialized/non-specialized in green incumbents and start-ups respectively. Given a time period of 22 years, the total number of states is thus 8,822. Ultimately, the social sequences analyses contribute, on the one hand, to revealing the uniqueness of green regional trajectories resulting from the specific duration and arrangement of green actor specializations. On the other hand, we are able to assess the resemblance of sequences and their contingencies. That is, the structural dynamics help to create typologies on the basis of all sequences (Gauthier, Bühlmann, and Blanchard 2014).

To reveal and analyze patterns among the sequences, we use optimal matching techniques. With these metric approaches, the distance between each pair of sequences is calculated as the minimum combination of replacement, insertion, and deletion of one sequence into the other

(Abbott 1995). These distances or resemblances are then clustered[2] to identify characteristic groups of regional trajectories, i.e. a typology of sequence trajectories (Brzinsky-Fay and Kohler 2010; Gauthier, Bühlmann, and Blanchard 2014). For selecting the optimal number of clusters we follow Studer (2021) who suggests parametric bootstrapping. This approach is particularly helpful to validate the observed typology by comparing it to clusters obtained from similar but non-clustered data. Overall, the clustering of regional trajectories allow a more holistic view on green actor specializations over time.

4. Results

The results section is structured along three main analytical steps. First, we provide an overview of the regional specializations with green incumbents and start-ups over time. This is followed by the identification and mapping of distinct types of regional trajectories based on their similarity using clustering methods. In a final step, we characterize the identified types by means of socio-economic data.

4.1 Regional development of eco-innovation specialization

To reveal regional development patterns that result from the annual calculation of the regions' green incumbent and green start-up specialization and the corresponding assignment to one of the four types of specialization (see Table 1), sequence-analytical methods help to make these cross-sectional distributions comparable through visualization techniques (Brzinsky-Fay and Kohler 2010; Gauthier, Bühlmann, and Blanchard 2014). More precisely, we make use of so-called index plots, where each line (sequence) represents the course of green actor

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[2] In this study, we make use of Ward hierarchical clustering methods. However, the results are also robust to other methods of clustering, such as partitioning or divisive analyses (e.g. Gabadinho et al. 2011; González-Leonardo, Newsham, and Rowe 2023).

specializations of a specific region. These index plots are shown in Figure 1, distinguishing between unsorted sequences (left) and sequences sorted by start and end (center and right).

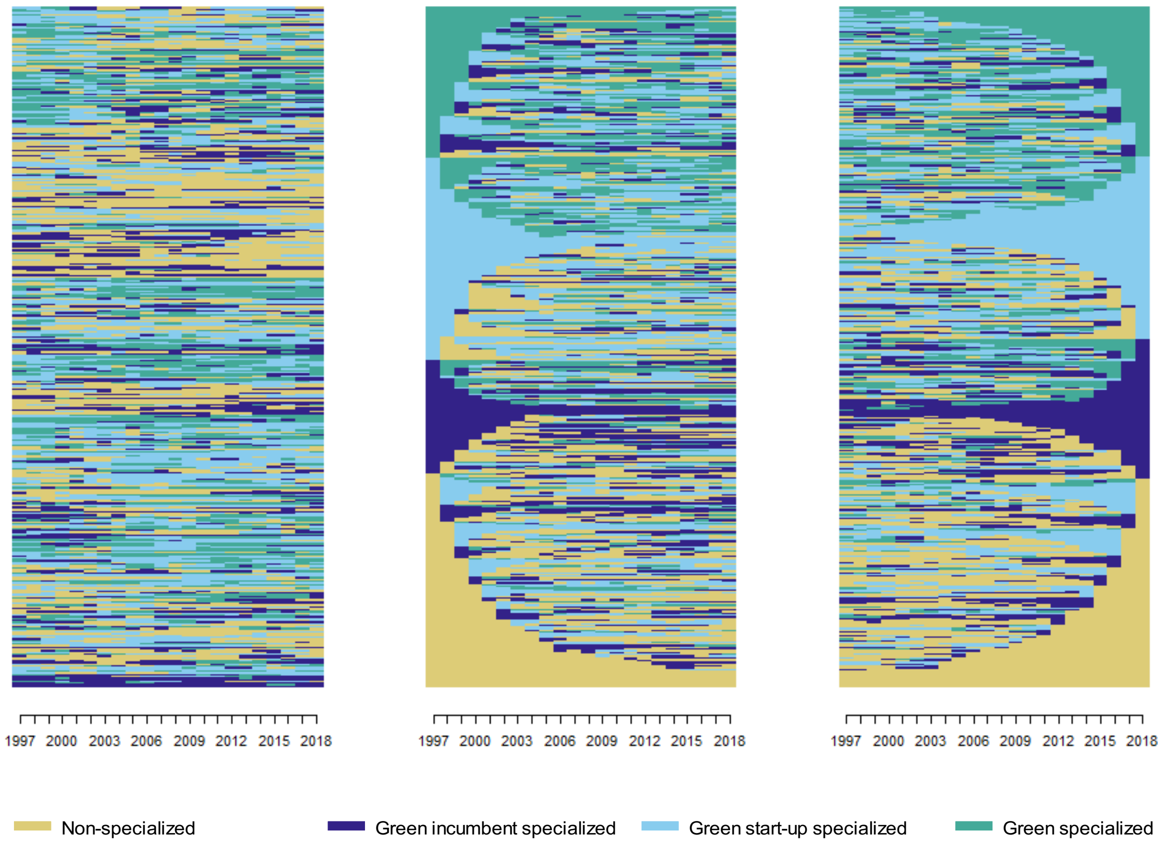

Figure 1: Region-specific specializations with eco-innovation actors over time

A first key finding that emerges from the comparison of the 401 regions over 22 years is the diversity of development patterns. Put differently, regions predominantly follow distinct trajectories with regard to the specific prevalence of eco-innovation actors. Of the 401 regional pathways, only 14 are identical (about 3.5 percent). Most of these are regions that show no specialization over the entire period. At first glance, the diversity of regional development patterns seems not surprising given a total number of around 8,800 states, each with four possible types of specialization. On the other hand, it must be kept in mind that we have included patent and start-up counts of the previous two years (moving windows) to calculate the annual specialization, which would suggest convergence of the regional patterns.

Remarkably, the annual share of each of the four types remains stable over time, with about 30 percent of the regions showing either no green specialization or green start-up specializations, while about 20 percent of the regions are green incumbent or green specialized. The mean time of specialization supports these findings. Over the whole observation period, regions have been non-specialized as well as start-up specialized for an average of 7 years, while an incumbent and green specialization averages only 4-5 years (see Figure A1 in the appendix).

When sorting regions by start and end state, their unique pathways can be traced more clearly (see again Figure 1). One of the most characteristic patterns is that there are hardly any changes from a previously non-specialization to a green specialization and vice versa. Rather, regions that were originally driven by green start-ups or green incumbents specialize differently, with a larger proportion remaining non-specialized. Conversely, non-specialized regions remain stable or eventually becoming dominated by only one of the two types of actors. Regions that become green-specialized over time are often previously green start-up specialized. These findings suggest that the greening of regions is often, though not necessarily, driven by start-ups before incumbents take up green activities. However, in order to explain green regional development in more detail, the patterns that emerge from the visualization require complementary analyses.

4.2 Different types of eco-innovation trajectories

After having identified a great variety of regional development patterns, we are particularly interested in assessing long-term trends among the regions, i.e. similarities of regional eco-innovation trajectories. As explained in section 3.3, cluster analyses allow to delineate distinct types of regions given their development of eco-innovation specialization. Overall, we identify six distinct types of regions using optimal matching techniques based on a Ward algorithm (see Figure 2). While four types have stable trajectories that essentially correspond to the aforementioned specialization dimensions, some regions in fact develop green specializations over time. Interestingly, this greening seems to be either induced by green incumbents or by green start-ups. We devote particular attention to these regions at the end of this section.

63 of the 401 regions (16 percent) follow an incumbent-driven trajectory (“green incumbent regions”). These regions are incumbent specialized for almost the entire period, meaning that green regional path development is mainly happening through established actors developing green technologies. In the years without incumbent specialization, which occur irregularly, this type of region is mostly showing no specialization at all. Consistently, specialization with both types of actors is less likely.

“Green start-up regions” are those in which green start-up but no incumbent specializations can be observed. These include 98 regions, i.e. about a quarter of the total sample. The fact that more regions are start-up than incumbent specialized is in line with their higher relative frequency (see again Figure A1). Over the years, only individual deviations can be observed in this trajectory, with the other three specializations occurring with roughly the same intensity.

Regions that follow a non-specialized trajectory are the most common (roughly 29 percent). As can be anticipated from Figure 1, this type of region only deviates, if at all, into green start-up or incumbent specialization. Overall, the development of “non-specialized regions” is quite stable. This persistence suggests how difficult it is for many regions to induce any long-lasting green activities to an above-average extent.

With a share of just over 10 percent, only 43 regions are permanently green-specialized. Apart from a few years with green start-up or incumbent specialization, regions of this trajectory are characterized by both green activities from existing and new actors. In contrast to green incumbent and green start-up trajectories, where a below-average specialization of both types of actors is occasionally evident, this is almost never the case in “green regions”. This suggests that regions of this type have reached a fairly stable level of eco-innovation output, with little intervening fluctuations.

Beyond the described stable regional trajectories - incumbent, start-up, non-specialized and green regions - about one fifth of the regions are characterized by a rather transitory development. These include, on the one hand, regions whose greening over time starts from green incumbent specialization (n=29) and, on the other hand, regions whose greening results from an earlier green start-up specialization (n=52). Consistent with the literature, these results indicate that the greening in regions may either start from incumbents who induce green start-ups via spillover effects and other transfer mechanisms (e.g., Corradini 2019; Colombelli and Quatraro 2019) or, vice versa, from green start-ups and newcomers who trigger change of established actors (e.g., Dewald and Achternbosch 2016; Yap et al. 2022). In our case, however, the more common path of greening seems to be via start-ups. On average, regions start to green around 2010, some a few years earlier, others a little later. Interestingly, the transition phase in particular is characterized by fluctuations in specialization, with regions being non-specialized in individual years becoming less likely. A change to the other type of main green actor, on the other hand, can be observed more frequently. In recent years, however, these regions seem to have stabilized in eco-innovation activities of both actor groups at above-average rate.

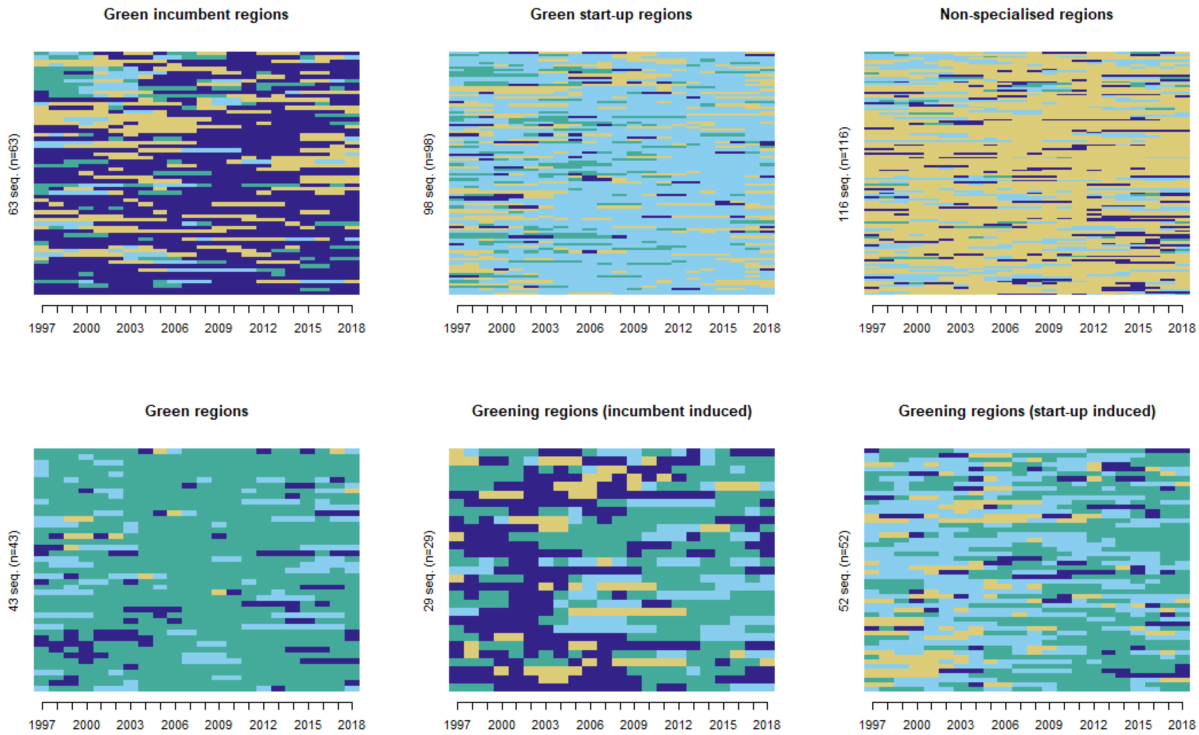

Figure 2: Different types of regional eco-innovation trajectories

By mapping the types of regional eco-innovation trajectories, we are able to reveal further characteristics beyond the temporal development (see Figure 3). What stands out from the geographical distribution in eco-innovation specialization are northeast and southwest differences. As such, regions in the eastern and northern parts of Germany tend to follow mainly green trajectories, while regions in the west and south are more often non-specialized. In contrast, start-up and incumbent regions are spread across the country, with the latter seeming to occur mainly in urbanized regions. Consistently, a start-up trajectory is more prevalent in rural areas. Against this background, it is striking that none of the metropolitan areas shows a start-up specialization and thus cannot be classified as green-specialized. Given that start-ups usually benefit from agglomeration advantages, this result seems counterintuitive at first. However, one must keep in mind that we are looking at the relative importance of eco-innovation actors. Accordingly, we conclude that the higher number of start-ups in densely populated regions offsets their share of green ones. Finally, those regions that have moved towards green specialization over the years, both incumbent and start-up-induced, are again more likely to be found in rural regions of the south and east.

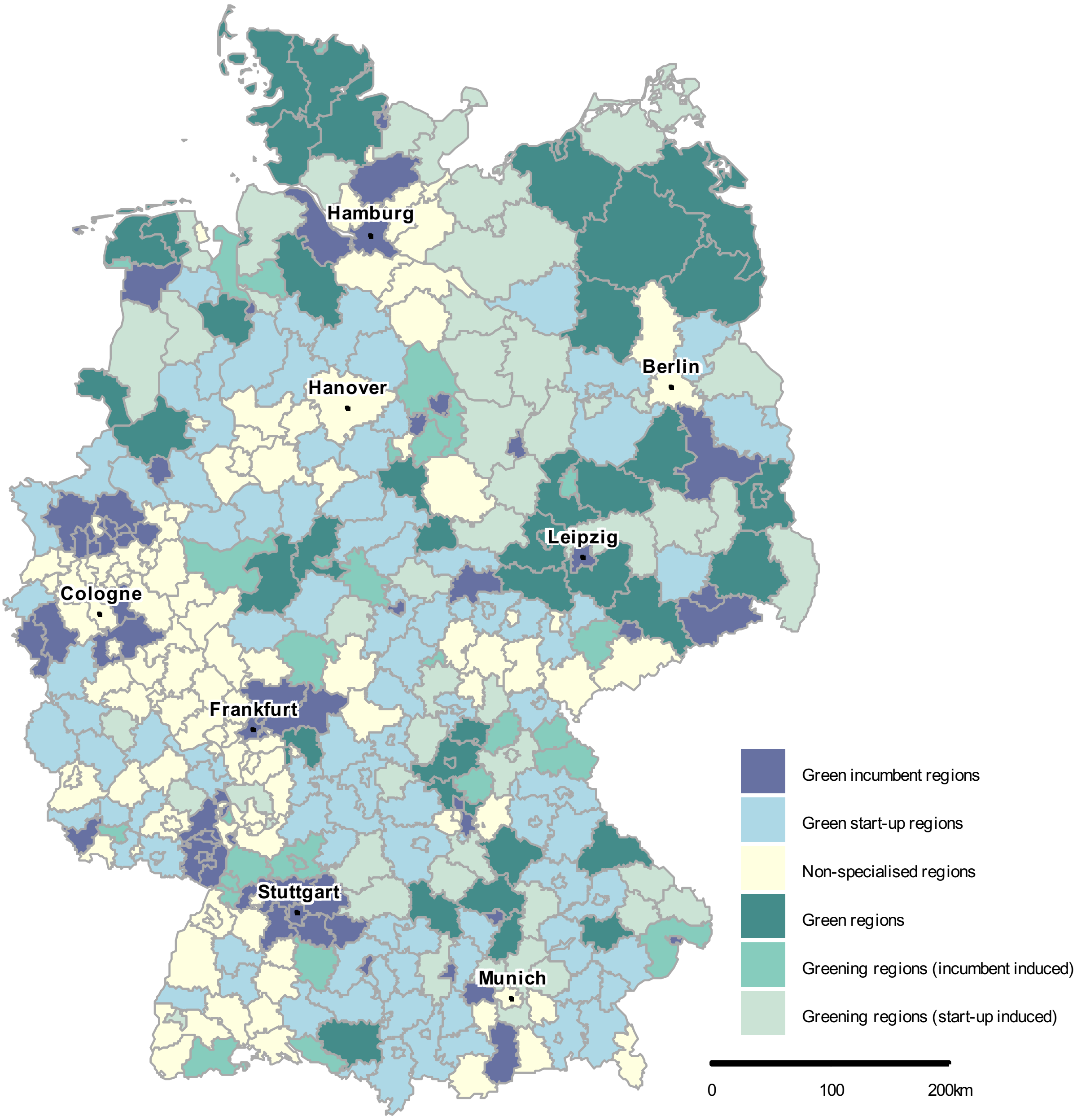

Figure 3: Geographical distribution of the different eco-innovation trajectories

In line with the spatial distribution of the individual eco-innovation trajectories, it is noticeable that neighboring regions often show equal development patterns. This seems to be particularly true with regard to green regions in the east and along the coast, incumbent regions around Stuttgart, Frankfurt, Hamburg and the Ruhr area, non-specialized regions between

Cologne and Frankfurt, and start-up regions in a central north-south axis. To control for spatial autocorrelation, we follow González-Leonardo et al. (2023) and run binary join count statistics, where the presence of a specific trajectory is tested against a random distribution. We find that the spatial joins of each trajectory, except for those regions where greening is induced via incumbents, is positively autocorrelated at the regional level (see Table A2 in the appendix). That is, regions of the same trajectory show a higher spatial co-occurrence than would be expected by chance. In addition, there is a significant spatial clustering between the various trajectories. For example, green start-up regions and start-up induced greening regions increasingly occur in spatial proximity to green regions. On the other hand, there are negative spatial dependencies. As would be expected, non-specialized and both green and greening regions are (with decreasing intensity) significantly less likely to be adjacent. Remarkably, this negative correlation also holds for green incumbent and start-up regions. The sequence-analytical results of this study thus ultimately reveal not only temporal patterns but also spatial ones, the latter supporting Tobler's (1970, 42) fundamental law that "everything is related to everything else, but near things are more related than distant things”.

4.3 Characterizing the different types of regions

To further validate the spatio-temporal patterns of regional eco-innovation specializations, we aim in a final step to characterize the six distinct types of regions. For this purpose, we draw on recent socio-economic data that help to detect trajectory-specific characteristics of the 401 regions. We do not claim to reveal correlations or even causalities in that regard. Instead, our results help to provide initial insights of possible influencing factors that require further in-depth analyses.

Figure 4 illustrates the aforementioned observation that green incumbent regions (IR) have a significantly higher population density, i.e. are more urban on average, compared to the other trajectories. Accordingly, green start-up regions (SR) and green regions (GR) are significantly more rural in character. Greening regions, both incumbent (GRi) and start-up (GRs) induced, also have a lower urbanization rate, while outliers in non-specialized regions (NR) explain their slightly higher population density. These findings are somewhat contrary to previous studies which have assumed that rural regions face particular challenges in generating and growing eco-innovation activities, especially green start-ups, across industries. Thin RIS structures, which are characteristic for rural regions, do thus not necessarily seem to be disadvantageous for eco-innovation emergence. Their number may be lower, but the relative importance often is not.

Looking at the unemployment rate, a second interesting pattern emerges. Green start-up regions have with about three percent by far the lowest unemployment rate, suggesting that a prosperous labor market is particularly conducive to the creation of novel green businesses. The higher unemployment rate of green incumbent regions (approx. five percent) at the same time averages that of green and greening regions, as these by definition have specialization in both types of actors.

In terms of regions' economic prosperity (GDP per employee), there is little variance between the trajectories, apart from striking outliers in the incumbent regions, suggesting increased value added by headquarters of large enterprises. Much more remarkable at first glance is that green regions appear to generate the lowest monthly median income (about 3,500 USD [3,000 EUR]). However, many of the green regions are located in eastern Germany (see Figure 3), which is still characterized by lower economic prosperity and average incomes. Greening regions are roughly equivalent to their related actor specialization, with green start-up regions having a lower median income than green incumbent regions.

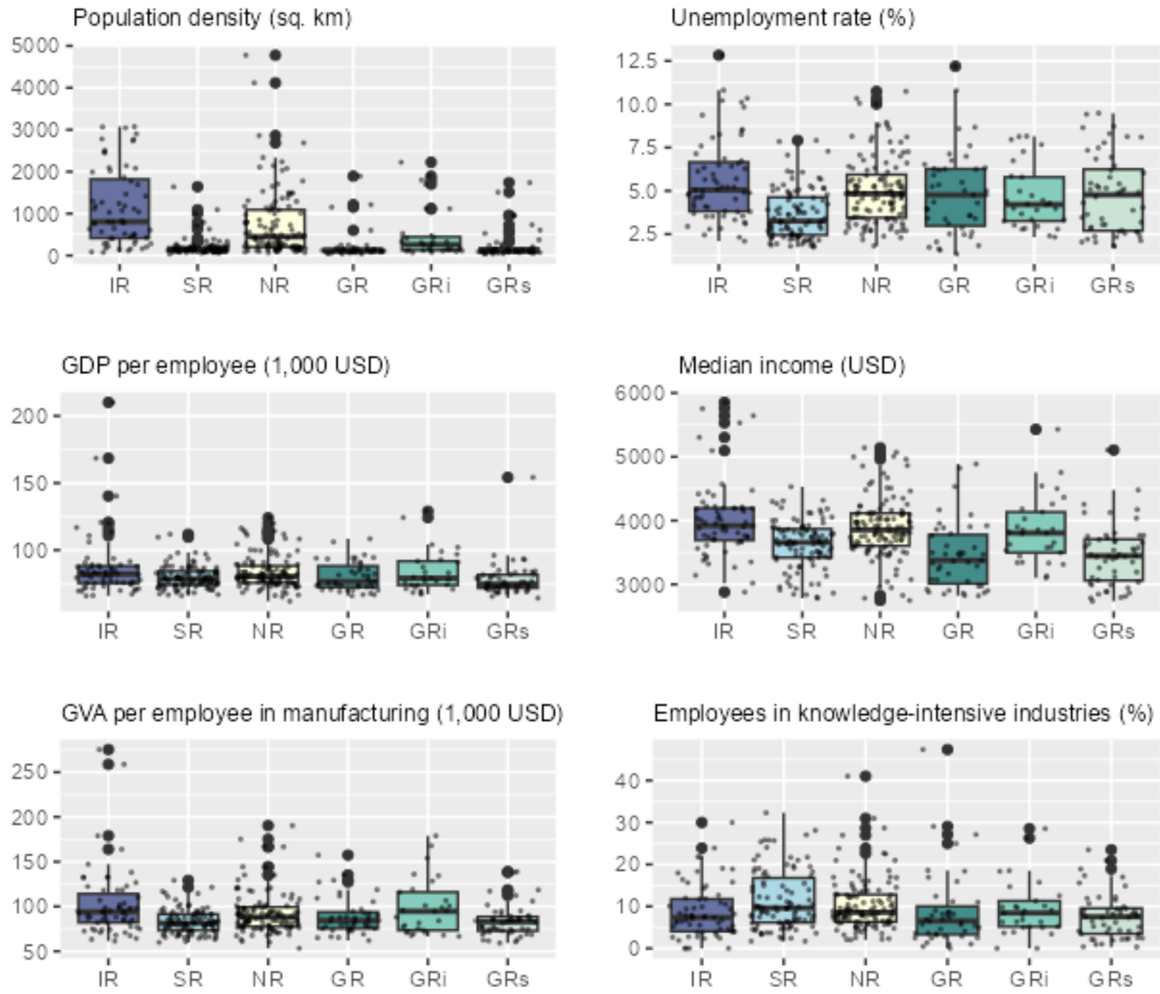

Figure 4: Socio-economic characterization of regional eco-innovation trajectories (data for 2019/2020; Federal Institute for Research on Building, Urban Affairs and Spatial Development, 2023)

In addition, the eco-innovation trajectories also differ significantly in terms of gross value added per employee in the manufacturing sector and employees' industrial background. Incumbent regions and those whose greening is induced by them are characterized by strong gross value added in potentially dirty sectors such as mining or construction. Conversely, these seem to offer less fruitful preconditions for green start-ups. Interestingly, this distribution changes when the share of employees in knowledge- and research-intensive industries is considered (chemical, pharmaceutical, electrical industries as well as mechanical and vehicle engineering sectors). Regions that are dominated by these industries seem to provide favorable conditions for green start-ups, but to a lesser extent stimulate green innovation activities of incumbents. The differences between both green or greening regions and incumbent regions are largely negligible.

Overall, it should be noted that across all indicators, the within-trajectory differences are often greater than those between the trajectories. This partly strong variance within the various types of eco-innovation specialization makes it harder to explain spatio-temporal patterns and categorize accordingly, calling for extensive in-depth analyses in future research.

5. Discussion

With the research objective of uncovering and comparing the eco-innovative development of regions over a long period of time, this study departs from previous work on green regional path development by not focusing on single regions' green technology or industry emergence, as usually done in case study designs. As such, we employ a broader approach that allows for the identification of differences and commonalities in green activities across multiple regions. Methodologically, we enrich economic geography research by introducing and applying sequence analysis methods. Doing so, we draw on a unique combination of green patent and start-up data for the 401 German NUTS-3 regions between 1997 and 2018, yielding a number of relevant insights that we believe help to advance recent and future EEG-informed debates on green path and place dependencies.

First, the relative importance of green start-ups and incumbents over time, i.e. the annual comparative advantage in eco-innovations, indicates that sustainability-oriented change is mainly unfolding heterogeneously among regions. Instead of unique development patterns, a multitude of annual fluctuations in specializations are evident, suggesting the influence of place-specific preconditions. Although we refrain from disentangling individual green development pathways, the patterns suggest that different economic activities are occurring that offset or reinforce each other (see also Jakobsen et al. 2022). Across all four dimensions of eco-innovation specialization, however, the proportion of regions with a green start-up specialization or no specialization predominates. The relative frequency of each state is largely constant over the entire period, which conversely means that regions are less likely to have a green or green incumbent specialization.

Second, despite distinct green development patterns at the regional level, the sequence analysis reveals strong similarities between different regional pathways. Overall, clustering methods suggest six different types of eco-innovation trajectories. In our case, about 80 percent of the regions follow largely stable trajectories that correspond to one of the four specialization dimensions. In line with the main assumptions of EEG, it can be thus concluded that differences in eco-innovation activities are subject to strong spatio-temporal persistence (e.g. Essletzbichler and Rigby 2007; Boschma and Frenken 2011). Hence, green regional development is expected to be rather gradual and less radical, as also evidenced by the fact that those regions that follow non-specialized trajectories hardly show any green specialization and vice versa. Disruptive path developments, as they are actually required in the context of addressing ecological challenges (Dawley 2014; Capasso et al. 2019; Jakobsen et al. 2022), thus seem to be the exception. And indeed, developments towards an above-average green incumbent and green start-up specialization can only be identified for one fifth of the regions. This greening results from a previous specialization in either of the two types of actors. Although we do not study the detailed mechanisms behind the greening trajectories, the observed patterns suggest that certain forms of related knowledge, assets and capabilities induce the respective other actor's green activities. Once again, these results are consistent with previous studies that consider relatedness as a main driving force of path and place dependencies, even when the focus is not on individual green technologies or green industries (e.g. Tanner 2014; MacKinnon et al. 2019; Santoalha and Boschma 2021)

Third, in a similar vein, our results indicate trajectory-specific spatial patterns. We find that neighboring regions often follow the same or similar trajectories. That is, green and greening types of regions occur in spatial proximity to each other, whereas non-specialized regions are on average spatially distant to green types of regions. Surprisingly, this negative dependency also exists between green incumbent and green start-up regions. In general, green and greening regions tend to occur in the north and east of Germany, while non-specialized regions are mainly located in the west. We interpret the fact that geographical proximity matters as the presence of spatially sensitive knowledge spillovers and diffusion of eco-innovation related activities, supporting previous studies (Binz, Truffer, and Coenen 2016; Colombelli and Quatraro 2019; Losacker 2022). At the same time, these phenomena also suggest the existence of (green) regional innovation systems, which obviously transcend the district level considered in this study.

Finally, we relate to the regions' socio-economic constitution that allow to characterize the six types of eco-innovation trajectories. At the same time, we are able to compare our types of regions with that of Grillitsch and Hansen (2019). In fact, green path developments seem to differ between urban and rural regions. The density of actors and diversity of innovation activities in urban areas does, apparently, not lead to an above-average specialization in green activities in these regions. Rather, established actors seem to be driving green activities in these regions. Conversely, in peripheral regions, which are generally considered to have weak capacities to develop green paths (Tödtling, Trippl, and Frangenheim 2020; Trippl et al. 2020), there is an above-average number of both green start-up and green incumbent activities. Thin RIS structures and a lower economic prosperity than average (cf. GDP in Figure 4) are not per se barriers to green regional trajectories. Overall, however, the results must be interpreted with caution, as we do not distinguish the actual impact of eco-innovations. This also applies to the influence of green and dirty specializations on green regional development. First indications are that the greening of regions is induced by green start-ups or green incumbents, suggesting that a critical mass of green activities is necessary to achieve broader sustainable change (Grillitsch and Hansen 2019). The influence of dirty industries also remains rather vague. However, exemplary reference can be made to historical coal regions, such as the Ruhr region, which have obviously managed to have established actors who pursue green innovation activities. Accordingly, dirty specialization need not be an obstacle, although green start-up activities are less evident, suggesting certain lock-in effects.

6. Conclusions

As one of the first studies in economic geography, we set out to investigate the development of eco-innovation activities across regions and over a long period of time. The main objective of this study was thus to gain generalizable insights into the unfolding of green regional development beyond the literature's prevalent focus on individual green industries and green technologies. Methodologically, we complemented existing case study approaches by using novel sequence analytical approaches for a unique set of regionally and annually assigned green patent and green start-up data. Instead of absolute eco-innovation measures, this study was designed to determine the relative importance of green incumbent and green start-up activities, ensuring a detailed and less biased regional comparison.

We have found that generally regions display largely distinct yet similar eco-innovation trajectories that allow to derive different types of regions. A large part of the regions show persistent specialization patterns over the entire period, manifested in trajectories with no specialization, a prevalence of either green incumbents or green start- ups, and a simultaneous above-average appearance of both actor types. As such, this study provides additional evidence for EEG's central assumptions of place and path dependency of economic activities. In a similar vein, the results suggest that the same types of regions appear in spatial proximity to each other, indicating systemic innovation dynamics across neighboring regions. Besides these rather stable green regional trajectories, only some regions seem to be able to establish above-average eco-innovation activities by both green incumbents and green start-ups over time. Most strikingly, this greening does not seem to unfold in a radical way, i.e. from a previous absence of any eco-innovation activities, but is rather induced by the respective other type of actor. These results complement those of previous studies, according to which a differentiated picture of the influence of past innovation activities on the development of regions emerges (Steen and Hansen 2018; Santoalha and Boschma 2021; Baumgartinger-Seiringer 2022). In general, typologies can be suitable to derive general patterns of regional development (e.g., Grillitsch and Hansen 2019), however, the identified heterogeneity of regions displaying similar trajectories suggests limits to classifications and the need for further validation.

While the present study represents an important step towards are broader understanding of green innovation development across regions, it is also subject to certain limitations. With the focus on uncovering general patterns, the underlying mechanisms that might explain the spatial differences remain unclear. Put differently, our study lacks insights to distinguish between path creation through new green industries or the restructuring of existing ones. In addition, technology- and industry-specific processes can overlap, reinforce or impede each other, especially given their multi-scalar interdependencies (Binz, Truffer, and Coenen 2016; Jakobsen et al. 2022). To better disentangle green regional development patterns, future work should thus consider the specificities of sectors and industries across diverse spatial contexts in more detail.

Similar to the limited evidence on preconditions and mechanisms, the potential effects of different eco-innovation specializations of regions remain vague. For example, a green specialized region may potentially contribute little to sustainable change, while conversely, non-specialized regions may have a high output of influential eco-innovations that are simply not evident in the variety of green activities. Against this background, it is also important to note that the relative eco-innovation importance does not necessarily reflect the actual progress, so it remains to be studied to what extent green path development processes really contribute to the environmental sustainability of economic production and consumption (Gibbs and Jensen 2022). Further research could usefully identify the emergence of radical eco-innovations or green industries and the resulting green regional path developments.

Taken together, we believe that future research in economic geography can benefit greatly from the empirical and methodological impulses provided in this study. Social sequence analyses are a valuable addition to the methodological portfolio, especially to trace trajectories over a long period of time and across diverse spatial context. In principle, a better understanding of a multitude of spatio-temporal phenomena ultimately also leads to valuable policy implications. In our case, path dependency and stability once again suggest that radical change is rather the exception. This makes it all the more important to understand the long-term nature and place-specificity of sustainable developments. By taking into account and promoting region-specific comparative advantages or focusing on unfavorable specialization patterns, we feel that sustainability challenges can be addressed in a more sophisticated way.

References

Abbott, A. 1995. Sequence Analysis: New Methods for Old Ideas. *Annual Review of Sociology* 21 (1):93–113. doi:10.1146/annurev.soc.21.1.93.

Abbott, A., and Tsay, A. 2000. Sequence Analysis and Optimal Matching Methods in Sociology: Review and Prospect. *Sociological Methods and Research* 29 (1):3–33. doi:10.1177/0049124100029001001.

Asheim, B.T., Grillitsch, M., and Trippl, M. 2016. Regional Innovation Systems : Past – Present – Future. In *Handbook on the Geographies of Innovation*, ed. R. Shearmur, C. Carrincazeaux, and D. Doloreux, 45–62. Cheltenham, Northampton: Edward Elgar Publishing.

Asheim, B.T., Smith, H.L., and Oughton, C. 2011. Regional Innovation Systems: Theory, Empirics and Policy. *Regional Studies* 45 (7):875–891. doi:10.1080/00343404.2011.596701.

Barbieri, N., Consoli, D., Napolitano, L., Perruchas, F., Pugliese, E., and Sbardella, A. 2023. Regional Technological Capabilities and Green Opportunities in Europe. *The Journal of Technology Transfer* 48:749–778. doi:10.1007/s10961-022-09952-y.

Baumgartinger-Seiringer, S. 2022. The Role of Powerful Incumbent Firms: Shaping Regional Industrial Path Development through Change and Maintenance Agency. *Regional Studies, Regional Science* 9 (1):390–408. doi:10.1080/21681376.2022.2081597.

Bersch, J., Gottschalk, S., Müller, B., and Niefert, M. 2014. *The Mannheim Enterprise Panel (MUP) and Firm Statistics for Germany*. *ZEW Discussion Paper*. Vol. No. 14-104. Mannheim. doi:10.2139/ssrn.2548385.

Binz, C., Truffer, B., and Coenen, L. 2016. Path Creation as a Process of Resource Alignment and Anchoring: Industry Formation for on-Site Water Recycling in Beijing. *Economic Geography* 92 (2):172–200. doi:10.1080/00130095.2015.1103177.

Boschma, R., and Frenken, K. 2006. Why Is Economic Geography Not an Evolutionary Science? Towards an Evolutionary Economic Geography. *Journal of Economic Geography* 6 (3):273–302. doi:10.1093/JEG/LBI022.

Boschma, R., and Frenken, K. 2011. The Emerging Empirics of Evolutionary Economic Geography. *Journal of Economic Geography* 11 (2):295–307. doi:10.1093/jeg/lbq053.

Brzinsky-Fay, C., and Kohler, U. 2010. New Developments in Sequence Analysis. *Sociological Methods and Research* 38 (3):359–364. doi:10.1177/0049124110363371.

Calignano, G., Fitjar, R.D., and Hjertvikrem, N. 2019. Innovation Networks and Green Restructuring: Which Path Development Can EU Framework Programmes Stimulate in Norway? *Norsk Geografisk Tidsskrift* 73 (1):65–78. doi:10.1080/00291951.2018.1561512.

Capasso, M., Hansen, T., Heiberg, J., Klitkou, A., and Steen, M. 2019. Green Growth – A Synthesis of Scientific Findings. *Technological Forecasting and Social Change* 146:390–402. doi:10.1016/j.techfore.2019.06.013.

Cojoianu, T.F., Clark, G.L., Hoepner, A.G.F., Veneri, P., and Wójcik, D. 2020. Entrepreneurs for a Low Carbon World: How Environmental Knowledge and Policy Shape the Creation and Financing of Green Start-Ups. *Research Policy* 49 (6):103988. doi:10.1016/j.respol.2020.103988.

Colombelli, A., and Quatraro, F. 2019. Green Start-Ups and Local Knowledge Spillovers from Clean and Dirty Technologies. *Small Business Economics* 52 (4). Small Business Economics:773–792. doi:10.1007/s11187-017-9934-y.

Cooke, P. 1992. Regional Innovation Systems: Competitive Regulation in the New Europe. *Geoforum* 23 (3):365–382. doi:10.1016/0016-7185(92)90048-9.

Cooke, P. 2012. Transversality and Transition: Green Innovation and New Regional Path Creation. *European Planning Studies* 20 (5):817–834.

doi:10.1080/09654313.2012.667927.

Corradini, C. 2019. Location Determinants of Green Technological Entry: Evidence from European Regions. *Small Business Economics* 52 (4):845–858. doi:10.1007/s11187-017-9938-7.

Dawley, S. 2014. Creating New Paths? Offshore Wind, Policy Activism, and Peripheral Region Development. *Economic Geography* 90 (1):91–112. doi:10.1111/ecge.12028.

Dewald, U., and Achternbosch, M. 2016. Why Did More Sustainable Cements Failed so Far? Disruptive Innovations and Their Barriers in a Basic Industry. *Environmental Innovation and Societal Transitions* 19:15–30. doi:10.1016/j.eist.2015.10.001.

Doblinger, C., Surana, K., and Anadon, L.D. 2019. Governments as Partners: The Role of Alliances in U.S. Cleantech Startup Innovation. *Research Policy* 48 (6):1458–1475. doi:10.1016/J.RESPOL.2019.02.006.

Eadson, W., and van Veelen, B. 2023. Green and Just Regional Path Development. *Regional Studies, Regional Science* 10 (1):218–233. doi:10.1080/21681376.2023.2174043.

Essletzbichler, J., and Rigby, D.L. 2007. Exploring Evolutionary Economic Geographies. *Journal of Economic Geography* 7 (5):549–571. doi:10.1093/jeg/lbm022.

Eurostat. 2014. *Patent Statistics at Eurostat: Mapping the Contribution of SMEs in EU Patenting. Eurostat Manuals and Guidelines - 2014 Edition*.

Gabadinho, A., Ritschard, G., Müller, N.S., and Studer, M. 2011. Analyzing and Visualizing State Sequences in R with TraMineR. *Journal of Statistical Software* 40 (4).

Gauthier, J.-A., Bühlmann, F., and Blanchard, P. 2014. Introduction: Sequence Analysis in 2014. In *Advances in Sequence Analysis: Theory, Method, Applications*, ed. P. Blanchard, F. Bühlmann, and J.-A. Gauthier. Vol. 2. Heidelberg New York Dordrecht London: Springer International Publishing. doi:10.1007/978-3-319-04969-4.

Gibbs, D., and Jensen, P.D. 2022. Chasing after the Wind? Green Economy Strategies, Path

Creation and Transitions in the Offshore Wind Industry. *Regional Studies* 56 (10):1671–1682. doi:10.1080/00343404.2021.2000958.

Giudici, G., Guerini, M., and Rossi-Lamastra, C. 2019. The Creation of Cleantech Startups at the Local Level: The Role of Knowledge Availability and Environmental Awareness. *Small Business Economics* 52 (4):815–830. doi:10.1007/s11187-017-9936-9.

González-Leonardo, M., Newsham, N., and Rowe, F. 2023. Understanding Population Decline Trajectories in Spain Using Sequence Analysis. *Geographical Analysis*, 1–22. doi:10.1111/gean.12357.

Grillitsch, M., and Hansen, T. 2019. Green Industry Development in Different Types of Regions. *European Planning Studies* 27 (11):2163–2183. doi:10.1080/09654313.2019.1648385.

Grillitsch, M., and Sotarauta, M. 2019. Trinity of Change Agency, Regional Development Paths and Opportunity Spaces. *Progress in Human Geography*, 1–20. doi:10.1177/0309132519853870.

Haščič, I., and Migotto, M. 2015. *Measuring Environmental Innovation Using Patent Data*. 89 OECD Environment Working Papers. OECD Environment Working Papers. Paris. doi:10.1787/5js009kf48xw-en.

Heimeriks, G., and Boschma, R. 2014. The Path- and Place-Dependent Nature of Scientific Knowledge Production in Biotech 1986-2008. *Journal of Economic Geography* 14 (2):339–364. doi:10.1093/jeg/lbs052.

Henning, M. 2018. Time Should Tell (More): Evolutionary Economic Geography and the Challenge of History. *Https://Doi.Org/10.1080/00343404.2018.1515481* 53 (4). Routledge:602–613. doi:10.1080/00343404.2018.1515481.

Horbach, J., Chen, Q., and Vögele, S. 2014. Do Lead Markets for Clean Coal Technology Follow Market Demand? A Case Study for China, Germany, Japan and the US.

Environmental Innovation and Societal Transitions 10 (March):42–58. doi:10.1016/J.EIST.2013.08.002.

Isaksen, A., and Trippl, M. 2016. Path Development in Different Regional Innovation Systems. In *Innovation Drivers and Regional Innovation Strategies*, ed. D.M. Parrilli, R.D. Fitjar, and A. Rodríguez-Pose, 1st ed., 240. Routledge. doi:10.4324/9781315671475.

Jakobsen, S., Uyarra, E., Njøs, R., and Fløysand, A. 2022. Policy Action for Green Restructuring in Specialized Industrial Regions. *European Urban and Regional Studies* 29 (3):312–331. doi:https://doi.org/10.1177/09697764211049116.

Kollmann, T., Strauß, C., Pröpper, A., Faasen, C., Hirschfeld, A., Gilde, J., and Walk, V. 2022. *German Startup Monitor*.

Kuebart, A. 2022. Open Creative Labs as Functional Infrastructure for Entrepreneurial Ecosystems: Using Sequence Analysis to Explore Tempo-Spatial Trajectories of Startups in Berlin. *Research Policy* 51 (9):104444. doi:10.1016/J.RESPOL.2021.104444.

Losacker, S. 2022. "License to Green": Regional Patent Licensing Networks and Green Technology Diffusion in China. *Technological Forecasting and Social Change* 175 (121336). doi:10.1016/j.techfore.2021.121336.

Losacker, S., and Liefner, I. 2020. Regional Lead Markets for Environmental Innovation. *Environmental Innovation and Societal Transitions* 37. Elsevier B.V.:120–139. doi:10.1016/j.eist.2020.08.003.

MacKinnon, D., Dawley, S., Steen, M., Menzel, M.P., Karlsen, A., Sommer, P., Hansen, G.H., and Normann, H.E. 2019. Path Creation, Global Production Networks and Regional Development: A Comparative International Analysis of the Offshore Wind Sector. *Progress in Planning* 130:1–32. doi:10.1016/j.progress.2018.01.001.

Martin, H., Martin, R., and Zukauskaite, E. 2019. The Multiple Roles of Demand in New Regional Industrial Path Development: A Conceptual Analysis. *Environment and*

Planning A 51 (8). doi:10.1177/0308518X19863438.

Martin, R., and Sunley, P. 2006. Path Dependence and Regional Economic Evolution. *Journal of Economic Geography* 6 (4):395–437. doi:10.1093/jeg/lbl012.

Neffke, F., Hartog, M., Boschma, R., and Henning, M. 2018. Agents of Structural Change: The Role of Firms and Entrepreneurs in Regional Diversification. *Economic Geography* 94 (1):23–48. doi:10.1080/00130095.2017.1391691.

Nelson, R.R., and Winter, S.G. 1982. *An Evolutionary Theory of Economic Change. The Economic Journal*. Cambridge, London: Harvard University Press. doi:10.2307/2232409.

Njøs, R., Sjøtun, S.G., Jakobsen, S.E., and Fløysand, A. 2020. Expanding Analyses of Path Creation: Interconnections between Territory and Technology. *Economic Geography* 96 (3). Routledge:266–288. doi:10.1080/00130095.2020.1756768.

Patias, N., Rowe, F., and Arribas-Bel, D. 2022. Trajectories of Neighbourhood Inequality in Britain: Unpacking Inter-Regional Socioeconomic Imbalances, 1971−2011. *Geographical Journal* 188 (2):150–165. doi:10.1111/geoj.12420.

Perruchas, F., Consoli, D., and Barbieri, N. 2020. Specialisation, Diversification and the Ladder of Green Technology Development. *Research Policy* 49 (3):103922. doi:10.1016/j.respol.2020.103922.

Pike, A., MacKinnon, D., Cumbers, A., Dawley, S., and McMaster, R. 2016. Doing Evolution in Economic Geography. *Economic Geography* 92 (2):123–144. doi:10.1080/00130095.2015.1108830.

Santoalha, A., and Boschma, R. 2021. Diversifying in Green Technologies in European Regions: Does Political Support Matter? *Regional Studies* 55 (2):182–195. doi:10.1080/00343404.2020.1744122.

Sotarauta, M., Suvinen, N., Jolly, S., and Hansen, T. 2021. The Many Roles of Change Agency in the Game of Green Path Development in the North. *European Urban and Regional*

Studies 28 (2):92–110. doi:10.1177/0969776420944995.

Steen, M., and Hansen, G.H. 2018. Barriers to Path Creation: The Case of Offshore Wind Power in Norway. *Economic Geography* 94 (2):188–210. doi:10.1080/00130095.2017.1416953.

Studer, M. 2021. Validating Sequence Analysis Typologies Using Parametric Bootstrap. *Sociological Methodology* 51 (2):290–318. doi:10.1177/00811750211014232.

Tanner, A.N. 2014. Regional Branching Reconsidered: Emergence of the Fuel Cell Industry in European Regions. *Economic Geography* 90 (4):403–427. doi:10.1111/ecge.12055.

Tanner, A.N. 2016. The Emergence of New Technology-Based Industries: The Case of Fuel Cells and Its Technological Relatedness to Regional Knowledge Bases. *Journal of Economic Geography* 16 (3):611–635. doi:10.1093/jeg/lbv011.

Tobler, W.R. 1970. A Computer Movie Simulating Urban Growth in the Detroit Region. *Economic Geography* 46:234–240. doi:10.1126/science.ns-13.332.462.

Tödtling, F., Trippl, M., and Desch, V. 2022. New Directions for RIS Studies and Policies in the Face of Grand Societal Challenges. *European Planning Studies* 30 (11):2139–2156. doi:10.1080/09654313.2021.1951177.

Tödtling, F., Trippl, M., and Frangenheim, A. 2020. Policy Options for Green Regional Development: Adopting a Production and Application Perspective. *Science and Public Policy* 47 (6):865–875. doi:10.1093/scipol/scaa051.

Trippl, M., Baumgartinger-Seiringer, S., Frangenheim, A., Isaksen, A., and Rypestøl, J.O. 2020. Unravelling Green Regional Industrial Path Development: Regional Preconditions, Asset Modification and Agency. *Geoforum* 111:189–197. doi:10.1016/j.geoforum.2020.02.016.

van den Berge, M., Weterings, A., and Alkemade, F. 2019. Do Existing Regional Specialisations Stimulate or Hinder Diversification into Cleantech? *Environmental Innovation and Societal Transitions* 35:185–201. doi:10.1016/j.eist.2019.10.002.

Yap, X., Truffer, B., Li, D., and Heimeriks, G. 2022. Towards Transformative Leapfrogging. *Environmental Innovation and Societal Transitions* 44:226–244. doi:10.1016/j.eist.2022.07.003.

Appendix

Table A1: Search terms to identify green start-ups in ZEW's MUP database

	Search terms
Energy	"photovoltaic", "pv", "solar", "solar energy", "solar power", "biogas", "bioreactor", "biomass", "bioenergy", "geothermal energy", "green electricity", "green power", "innovative energy products", "block heating", "wind energy", wind farm", "wind park", "wind power", "wind turbine", "heat pump", "tidal power station", "wave power station", "condensing boiler", "water turbine", "digestion tower", "pumped storage", "hydropower", "hydroelectric", "hydroelectric plant", "run-of-river power", "thermal power", "heat-power", "bioethanol", "biodiesel", "biofuel", "Btl-fuel", "biomass-to-liquid", "e-fuel", "hydrogen system", "hydrogen economy", "green hydrogen", "hydrogen grid", "power-2-gas", "power-to-gas", "power-2-X", "power-to-X", "green hydrogen", "battery module", "battery system", "battery storage", "battery cell" "Renewable Energies Act [EEG]", "energy optimization", "energy infrastructure", "energy data management", "energy transition", "energy efficiency", "power engineering", "energy storage", "energy standards", "electricity storage", "energy monitoring", "smart grid", "smart meter"
Transport	"electric car", "electric scooter", "e-scooter", "electric bus", "electric mobility", "electric vehicle", "hybrid car", "hybrid vehicle", "hybrid drive", "fuel cell", "car sharing", "shared mobility", "ridesharing", "carpooling", "fast charging", "e-charging station", "charging network", "charging infrastructure"
Building	"energetic building renovation", "renewable building material", "wooden building", "passive house", "energy saving house", "zero energy house", "low

	energy house", "energy certificate", "zero energy house", "low energy house", "insulation", "insulating material", "insulating effect", "thermal protection", "cold protection", "heat storage"
Air & Water	"carbon capture", "CCS", "CO2 sequestration", "carbon sequestration", "pollutant-free", "low-pollutant", "pollutant-reduced", "CO2-free", "CO2 neutral", "low-emission", "emission-free", "resource-saving", fine dust sensor", "particulate filter", "air pollution control", "air filter", "air cleaner", air cleaning", "air filtration", "pollutant remediation", "exhaust gas cleaning", "cleaning of exhaust gases", "removal of exhaust gases", "exhaust gas after-treatment", "noise protection", "noise control", "noise abatement", "noise remediation", "pond remediation", "lake remediation", "contaminated site remediation", "renaturation", "water remediation", "environmental remediation" "water saving", "water conservation", "water protection", "water pollution control", "water purification", "water filtration", "water treatment"
Waste	"recycling", "waste separation", "raw material recovery", "waste sorting plant", "waste recovery", "waste paper disposal", "environmental disposal", "raw material cycle", "circular economy", "reuse", "remanufacturing", "life cycle"
Services	"sustainability management", "environmental engineer", "environmental service", "environmental consulting", "energy consulting", "environmental protection management", "energy management", "energy coach", "sustainability strategy"
Other	"ecological", "environmentally friendly", "sustainable", "environmentally sound", "environmentally compliant", "environmentally related", "environmentally oriented", "environmentally compatible", "energy efficient",

"biogenic", "biological", "natural", "climate-friendly", "climate-compatible", "regenerative", "renewable", "reduce", "save", “avoid”

Please note: The terms shown here are translated from German and give an indication of the search strategy. Due to complex use of operators, word combinations -also across several words- and exclusion words, the search strategy cannot be depicted in its entirety. However, several consistency checks as well as manual sample checks of the identified companies led to robust results. The search strategy has been applied in several related research projects.

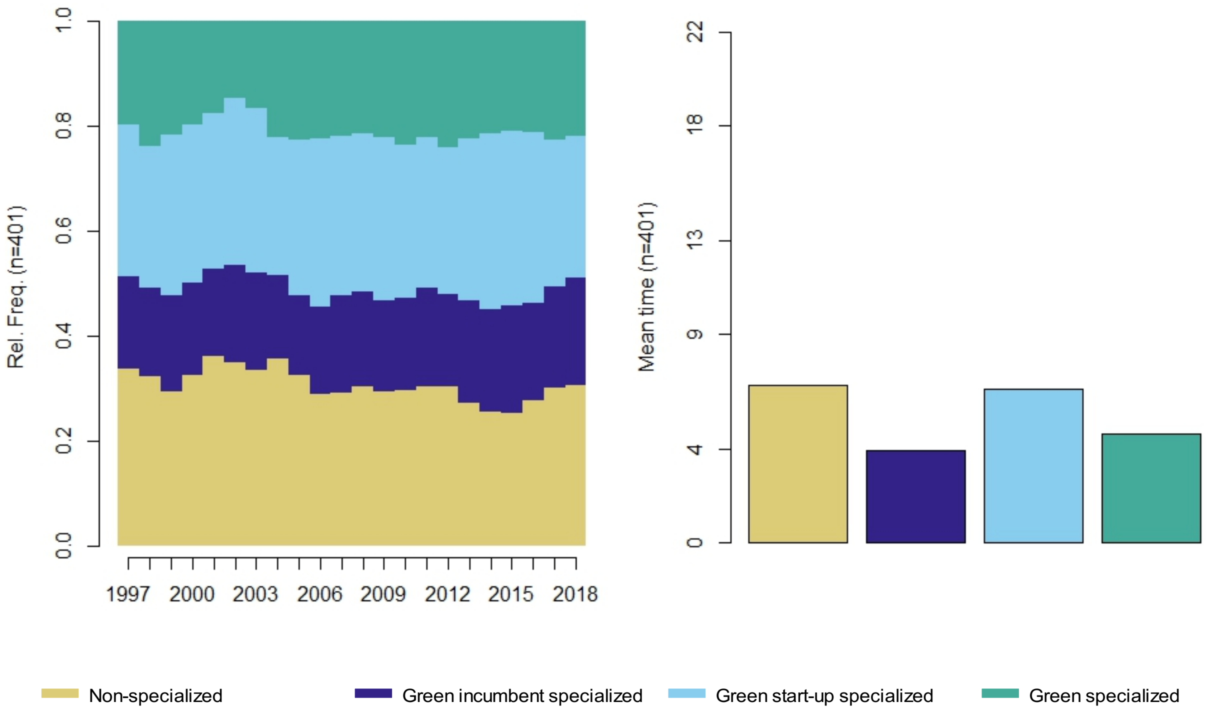

Figure A1: Relative frequency and mean time of regional eco-innovation specialization

Table A2: Matrix on spatial autocorrelation

		1	2	3	4	5	6
1	Green incumbent regions	1.92***					
2	Green start-up regions	0.51***	1.72***				
3	Non-specialized regions	0.87	0.95	1.43***			
4	Green regions	0.62**	1.33***	0.29***	2.46***		
5	Greening regions (Incumbent induced)	1.09	0.92	0.64***	0.98	1.13	
6	Greening regions (start-up induced)	0.61***	1.14	0.56***	1.78***	1.07	1.73***

The values express the ratio of observed and expected join counts, where values < 1 indicate negative spatial autocorrelation and values > 1 positive spatial autocorrelation (see also González-Leonardo et al (2023)).

Note: **p<0.05; ***p<0.01