Regional Perspectives on Eco-Innovation: Actors, Specialisations and Transition Trajectories

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Abstract

Tackling human-caused global warming and ecological degradation requires rapid transformative change in production and consumption patterns. In this regard, eco-innovations represent a cornerstone for reducing environmental burdens and strengthening sustainability. However, recent global efforts to scale up eco-innovations are confronted with strong spatial differences in their development and application. Against this background, the growing literature on the geography of innovation-based transformative change particularly emphasises the importance of regional specificities emanating mainly from institutions, technologies and actors.

While many studies have explored eco-innovations' enabling and constraining conditions at the regional level, scholarly debates lack insights into the extent to which eco-innovation activities in regions are carried out by incumbents or start-ups. Put differently, little is known about regional specialisations, i.e. regional comparative advantages, with regard to these two types of eco-innovation actors. This dissertation therefore sets out to gain a regionally nuanced understanding of the contribution of incumbents and start-ups to eco-innovation activities and its development over time. To ensure a broad and comparative perspective on green regional development, this research focuses on both sector-specific and general eco-innovation activities in German regions.

By systematically reviewing the extensive yet fragmented body of research that revolves around the geography of eco-innovations, this dissertation first reveals complementarities that harbour promising avenues for future research. These conceptual elaborations are then followed by empirical investigations on regional eco-innovation specialisations using a novel data set on green patents and green start-ups. The findings suggest heterogeneous and persistent specialisation patterns of regions, while it is rather the exception that eco-innovation activities in regions are driven by both established actors and start-ups. In order to foster eco-innovations, a sustainability-oriented innovation policy should take greater account of the heterogeneity and path dependency of regional actor specialisations.

Keywords: eco-innovations, sustainability transitions, regional specialisations, green regional development, incumbents, start-ups

Zusammenfassung

Zur Bewältigung der menschengemachten Erderwärmung und Umweltzerstörung ist ein rascher Wandel von Produktions- und Verbrauchsweisen unabdingbar. In dieser Hinsicht sind Umweltinnovationen ein Eckpfeiler für die Verringerung von Umweltbelastungen und die Stärkung der Nachhaltigkeit. Allerdings sehen sich aktuelle weltweite Bemühungen um eine Verbreitung von Umweltinnovationen starken räumlichen Unterschieden bei ihrer Entwicklung und Anwendung gegenüber. Vor diesem Hintergrund wird in der jüngeren Forschung zur Geographie innovationsbasierter Nachhaltigkeitstransformationen speziell die Bedeutung regionaler Besonderheiten betont, die insbesondere von Institutionen, Technologien und Akteuren ausgehen.

Während viele Studien förderliche und hinderliche Bedingungen für Umweltinnovationen auf regionaler Ebene untersucht haben, fehlt es bislang an Erkenntnissen, inwieweit diese Aktivitäten in Regionen von etablierten Akteuren oder Start-ups hervorgebracht werden. Anders ausgedrückt: Es ist wenig über regionale Spezialisierungen, d.h. regionale komparative Vorteile, dieser beiden Arten von Umweltinnovationsakteuren bekannt. Diese Dissertation beabsichtigt, ein regional differenziertes Verständnis zu Umweltinnovationsaktivitäten von etablierten Akteuren und Start-ups sowie deren Entwicklung im Zeitverlauf zu gewinnen. Um eine breite und vergleichende Perspektive auf die grüne Regionalentwicklung aufzuzeigen, fokussiert diese Forschung sowohl auf sektorspezifische als auch gesamte Umweltinnovationsaktivitäten in deutschen Regionen.

Durch eine systematische Aufarbeitung des umfangreichen, aber fragmentierten Forschungsstands zur Geographie von Umweltinnovationen deckt diese Dissertation zunächst Komplementaritäten auf, die vielversprechende Wege für künftige Forschung eröffnen. Diesen konzeptionellen Ausarbeitungen folgen empirische Untersuchungen zu regionalen Spezialisierungen in Umweltinnovationen unter Verwendung eines neuartigen Datensatzes zu grünen Patenten und grünen Start-ups. Die Ergebnisse deuten auf heterogene und persistente Spezialisierungsmuster von Regionen hin. Eher die Ausnahme ist, dass Umweltinnovationsaktivitäten in Regionen sowohl von etablierten Akteuren als auch Start-ups getrieben werden. Um Umweltinnovationen zu fördern, sollte eine nachhaltigkeitsorientierte Innovationspolitik die Heterogenität und Pfadabhängigkeit von regionalen Akteursspezialisierungen stärker berücksichtigen.

Schlagworte: Umweltinnovationen, Nachhaltigkeitstransitionen, regionale Spezialisierungen, grüne Regionalentwicklung, etablierte Akteure, Start-ups

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„Der Schutzauftrag des Art. 20a GG schließt die Notwendigkeit ein, mit den natürlichen Lebensgrundlagen so sorgsam umzugehen und sie der Nachwelt in solchem Zustand zu hinterlassen, dass nachfolgende Generationen diese nicht nur um den Preis radikaler eigener Enthaltsamkeit weiter bewahren könnten.“

BVerfG, Beschluss des Ersten Senats vom 24. März 2021 - 1 BvR 2656/18 -, Rn. 1-270

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PART ONE: INTRODUCTION

1 Motivation

Unsustainable human activities have led to an unprecedented acceleration of climate change as well as related biodiversity losses and damages to ecosystems. In particular, continued anthropogenic greenhouse gas (GHG) emissions, estimated at 59 $GtCO_2$-eq in 2019, have increased the mean global surface temperature by more than 1°C compared to the second half of the nineteenth century. As global warming directly affects weather and climate extremes, mitigation of and adaptation to climate change are crucial to reduce human and ecosystem vulnerability (IPCC 2023).

Despite decades of scientific knowledge generation on climate change and associated risks, concrete policy action at the international level has gained momentum only in more recent years. Of particular importance is the Paris Agreement (UNFCCC 2016), adopted in 2015, which has been ratified by almost the entire international community of states and sets legally binding climate targets. According to Article 2 of the treaty, the main objective is to keep global warming to well below 2°C and to pursue efforts to limit it to 1.5°C above pre-industrial levels. To achieve this, IPCC's (2023) latest assessment report on climate change once again emphasises the need for rapid and sustained reductions in GHG emissions through far-reaching transformative change across all sectors. Although recent progress has been made to address environmental challenges, with some countries aiming for climate neutrality by mid-century (see, e.g., the European Green Deal (European Commission 2019)), an upscaling of climate action is required.

While the targeted systemic transformations involve multiple mitigation and adaptation options, innovations are undoubtedly among the essential ones. These include, for example, technological solutions such as renewable energies, material and energy efficiency improvements through innovative production processes and demand-side management, and new services in various sectors that transform established modes of production and consumption. However, the potential for developing and adopting innovations aimed at environmental sustainability - hereafter referred to as eco-innovations - is highly dependent on social, economic, institutional and political conditions at national and sub-national levels (Cooke 2011; Coenen, Hansen, and Rekers 2015; IPCC 2023).

It is precisely these differences in spatial manifestations of eco-innovation activities that are of fundamental research interest in burgeoning strands of research within economic geography, innovation studies and related disciplines. Over more than a decade, numerous conceptual and empirical studies have highlighted the systemic nature of eco-innovation processes (Cooke 2010; Truffer and Coenen 2012; Boschma et al. 2017). Particular attention has been paid to a variety of enabling and constraining conditions at different spatial scales and across sectors, resulting in rather fragmented scholarly debates. At the same time, however, the different research streams stress the importance of place specificities and geographical proximity that essentially influence eco-innovation activities and related transformative change. As such, recent studies suggest that environmentally friendly products and practices are crucially influenced by region-specific technological specialisations, institutional and political frameworks, and actor constellations (Gibbs and O'Neill 2014; Hansen and Coenen 2015; Montresor and Quatraro 2020; Losacker, Horbach, and Liefner 2023). Similarly, evolutionary approaches emphasise path dependencies of green regional development (Njøs et al. 2020; Tödtling, Trippl, and Frangenheim 2020; Gibbs and Jensen 2022).

While it is now well recognised that the spatial unevenness of eco-innovation is largely determined by various drivers and barriers at the regional level, much less is known about the key actors that drive eco-innovation activities in different regional contexts. More precisely, it remains unclear by whom eco-innovative change is driven, especially when differentiating between established, i.e. incumbent, and novel actors. Without negating recent advances made on the multiplicity of actors and their agency (e.g., Trippl et al. 2020; Sotarauta et al. 2021), the ambition of this dissertation is thus to disentangle (long-term) regional specialisations in green incumbents and green start-ups. Taken together, this complementary regional perspective on the relative importance of eco-innovators strives to improve the understanding of the geography of sustainable change and to provide additional policy impetus to better address environmental challenges.

This dissertation is divided into three parts. Starting with the motivation, the first part introduces the theoretical background, research objectives and data and methods. In addition, it provides a brief description of both related and the foundational research contributions to this dissertation. The second part comprises the three research articles that form the backbone of this dissertation. The third part then draws conclusions across the research articles, consisting of the summary, main contributions and limitations as well as promising implications for (regional) innovation policy and future research.

2 Theoretical background and research objectives

The following section outlines the literature on the geography of eco-innovations and sustainability transitions that guides the research for this dissertation, followed by the derivation of the research questions.

2.1 The geography of innovation-based transitions towards environmental sustainability

Originating from the Schumpeterian notion of "new combinations" of resources and knowledge (Schumpeter 1934), innovation is considered a main driving force of economic development (Fagerberg, Fosaas, and Sapprasert 2012). Throughout the last decades, supplementary perspectives have complemented this economic rationale of innovation activities, including their pivotal role in addressing environmental challenges and achieving sustainable change. It is therefore hardly surprising that sustainability-oriented innovation has received broad scientific attention across disciplines, resulting in a multitude of labels and definitions (Boons and McMeekin 2019; Kemp et al. 2019). Like much previous research in innovation studies, this dissertation draws on the term eco-innovations, defined as "all measures of relevant actors [...] which develop new ideas, behaviour, products and processes, apply or introduce them and which contribute to a reduction of environmental burdens or to ecologically specified sustainability targets" (Rennings 2000, 322). In this way, eco-innovations deliberately go beyond technological solutions and also include changes in institutional, social and organisational structures.

The necessity of geographical perspectives on eco-innovations ultimately results from their spatial constitution. That is, eco-innovations are not solely determined by characteristics of the innovator (e.g., Horbach 2008; De Marchi 2012), but also shaped by place specificities and geographical context conditions. This systemic perspective is fundamental to the research on the geography of eco-innovations and related transformative change (Hansen and Coenen 2015; Binz et al. 2020; Losacker et al. 2023). To date, however, this field of research has remained largely fragmented, which is expressed in different research interests and methodological features. In principle, research contributions range from small-scale perspectives on the emergence of eco-innovations to broader sectoral perspectives on multi-scalar interdependencies that drive or prevent the upscaling thereof. Against this background, it is important to note that these two broader research directions do not represent opposing poles, as also shown by a growing body of literature that combines insights from innovation and transition studies (Boschma et al. 2017; Trippl et al. 2020; Gibbs and Jensen 2022). Yet, this delineation proves useful in structuring the diverse field of research.

Geographical research dealing with the emergence and development of eco-innovation emphasises the central importance of spatial proximity and (historically grown) regional characteristics. Accordingly, much of this literature conceptually draws on regional innovation systems (RIS) and evolutionary approaches within economic geography. The latter comprise, for example, concepts of regional branching and path creation, which particularly emphasise the role of pre-existing structures for future regional development (Tanner 2014; Tödtling, Trippl, and Frangenheim 2020). Although the focus is primarily on technological eco-innovations, so-called green technologies (Ghisetti and Quatraro 2017; Montresor and Quatraro 2020; Barbieri et al. 2023), research also looks at different types of eco-innovation. Of particular recent concern is the spatial dimension of green start-up emergence and its enabling regional characteristics (Giudici, Guerini, and Rossi-Lamastra 2019; Vedula, York, and Corbett 2019; Coll-Martínez, Malia, and Renou-Maissant 2022).

As has been demonstrated by extensive research in the past decade, eco-innovation is significantly influenced by localised knowledge bases and (inter-)regional spillover, learning processes as well as exchange processes and network relationships between (non-)firm actors (Cooke 2010; Antonioli, Borghesi, and Mazzanti 2016; Corradini 2019; Grillitsch and Hansen 2019; Bugge, Andersen, and Steen 2021). While these general spatial patterns also apply to other innovations, spatial context conditions are all the more important for eco-innovations for two reasons. First, data from previous studies suggest that eco-innovations are more complex and more novel, as evidenced by a higher number of diverse and unique knowledge recombination processes (Horbach, Oltra, and Belin 2013; Colombelli and Quatraro 2019; Barbieri, Marzucchi, and Rizzo 2020). Second, eco-innovations often constitute younger industries and technological domains, necessitating external, especially unrelated, sources of knowledge in close geographical proximity (Horbach 2014; Barbieri, Perruchas, and Consoli 2020; Fusillo 2023)

In line with the geography of innovation literature, technological capabilities are among the main drivers that stimulate the greening of regional economies. Eco-innovations are thus more likely to emerge when these are related to existing technologies and knowledge bases at the regional level (Montresor and Quatraro 2020; Moreno and Ocampo-Corrales 2022). In this respect, prior studies have also noted the importance of other knowledge-producing actors, such as universities and research institutes, in inducing green spin-offs and providing complementary skills and technological competences (Cainelli, Mazzanti, and Montresor 2012; Horbach 2014; Tanner 2014). All these processes of cumulative knowledge production are ultimately seen to facilitate green industrial developments. Contrary to expectations, empirical results suggest that knowledge inputs from unsustainable technological activities can also have a positive impact on eco-innovations. Regional specialisations in non-green industries are therefore not disadvantageous per se. They allow green paths to develop if green and non-green innovations are technologically related, as this facilitates knowledge recombination and spillovers (Quatraro and Scandura 2019; van den Berge, Weterings, and Alkemade 2019; Santoalha and Boschma 2021).

Similar to technological elements and knowledge, formal and informal institutions (North 1990) are found to (dis)incentivise eco-innovation activities. Informal institutions comprise, among others, norms, shared visions, behaviours and conventions, and form contextual conditions in which eco-innovation actors and their activities are embedded (Carvalho, Mingardo, and van Haaren 2012; Grillitsch and Hansen 2019; Sunny and Shu 2019). In this context, a few studies indicate that pro-environmental attitudes and community logics increase regional eco-innovations (Giudici, Guerini, and Rossi-Lamastra 2019; Bammens and Hünermund 2023). In contrast, green path developments can be hampered by institutional inertia and over-embeddedness, often found in highly specialised or old-industrial regions (Cainelli, Mazzanti, and Zoboli 2011; Tödtling, Trippl, and Frangenheim 2020). Besides these socio-cultural aspects, policies and regulations, i.e. formal institutions, are important instruments to strengthen eco-innovation activities. From an economic perspective, the legitimacy of policy interventions arises mainly from market failures associated with the so-called double externality problem of eco-innovations. Accordingly, private incentives to invest in environmentally friendly products and practices are low, as non-innovators benefit at no cost from both knowledge spillovers in the development phase and reduced environmental burdens in the diffusion phase (Rennings 2000; Capasso et al. 2019). Having said this, policy and regulatory support often only has a positive impact on regional eco-innovation activities if it takes into account place-specific industrial and institutional structures. This applies equally to policy action - emanating from the regions themselves or higher spatial scales - that targets the supply side (e.g., R&D investments, infrastructural measures) or demand side (e.g., public procurement, market formation) (Dawley 2014; Tödtling, Trippl, and Frangenheim 2020; Hansmeier and Losacker 2021; Jakobsen et al. 2022).

While the aforementioned research contributions mainly address the enabling regional conditions of eco-innovation emergence from an innovation economics perspective, a second direction of research focuses on the spatiality of eco-innovations in the context of broader socio-technical changes. As these so-called sustainability transitions comprise complex and multi-dimensional changes of sectoral production and consumption patterns (Markard, Raven, and Truffer 2012; Köhler et al. 2019), their geography is seen to depend on multi-scalar interdependencies. The unevenness of transition processes across space is thus not only a matter of place-specific conditions and local variations (Raven, Schot, and Berkhout 2012; Hansen and Coenen 2015; Chlebna, Martin, and Mattes 2022), but also due to wider technological, institutional and actor configurations across spatial scales (Truffer and Coenen 2012; Strambach 2017; Miörner and Binz 2021). In this regard, research on the geography of transitions pays little attention to the spatial conditions under which eco-innovations develop. Instead, it emphasises spatial contingencies that drive or prevent eco-innovation application and broader systemic change towards sustainability (van den Berge, Weterings, and Alkemade 2019; Binz et al. 2020).

Given the main interest of transitions research in uncovering the relationship between stabilising forces and change, much of the literature conceptually refers to niche-regime interactions inherent in the multi-level perspective (MLP) (Geels 2004; Köhler et al. 2019). Niches, in a non-geographical sense, are protected spaces where (radical) eco-innovations emerge through experimentation and learning processes without being exposed to selection pressures. Regimes, in contrast, are depicted as highly structured social and institutional entities in which knowledge, practices and technologies are embedded and seamlessly linked to dominant user expectations, competencies, markets and infrastructures. Embracing the "rules of the game", regimes are therefore stable and path-dependent, resulting in incremental and long-term socio-technical change (Geels 2004; Markard, Raven, and Truffer 2012;

Berggren, Magnusson, and Sushandoyo 2015). From a geographical perspective, the concepts were originally criticised for neglecting the spatial context or having a naïve understanding thereof (Coenen, Benneworth, and Truffer 2012). Although recent advances have been made that shed light on the multi-scalarity of stability and change (Rohe 2020; Miörner and Binz 2021), it still remains unclear to what extent regimes and niches confine themselves geographically. However, the prevalent perspective on systemic drivers and barriers helps to gain a spatially nuanced understanding of the impact of eco-innovations after their introduction.

In general, research on the geography of transitions emphasises the social constitution and construction of places, scales and spaces. Against the background of this relational and constructivist understanding of geography, numerous actors at different spatial levels exert influence on eco-innovation activities (Späth and Rohracher 2012; Hansen and Coenen 2015; Truffer, Murphy, and Raven 2015). Also of key importance from a demand-side perspective are usually non-innovative actors, such as societal actors and intermediaries, as they help to configure places and local contexts so that environmentally friendly alternatives can become increasingly institutionalised, adopted and embedded (Sjøtun and Njøs 2019; Loorbach et al. 2020). At the same time, however, eco-innovation and transformative change comprise normative and directional elements (Rennings 2000; Köhler et al. 2019), leading to disagreements and tensions between different groups of actors. Accordingly, it is generally assumed that actors who are closely intertwined with the current regime structures (e.g., multinational firms) hamper socio-technical change, while impulses towards sustainability tend to come from novel niches actors (e.g., start-ups) outside dominant systemic structures. Both groups of actors are not only characterised by a socio-institutional embeddedness in the broader sectoral environment, but are likewise strongly anchored at the regional level (Truffer and Coenen 2012; Dewald and Fromhold-Eisebith 2015; Fontes, Sousa, and Ferreira 2016).

This dissertation adopts this distinction between incumbent and novel actors (start-ups), well aware that the dichotomy of incumbents and challengers is increasingly questioned and that their agency is far more pluralistic than often conceptualised (e.g., Klitkou and Coenen 2013; Berggren, Magnusson, and Sushandoyo 2015; Turnheim and Sovacool 2019; Sotarauta et al. 2021). At the same time, the literature recognises that the formation of green start-ups and green activities of incumbents are two complementary pathways of eco-innovation emergence that are necessary to achieve green restructuring and systemic sustainability transitions (Corradini 2019; Giudici, Guerini, and Rossi-Lamastra 2019; Trippl et al. 2020). Up to now, however, there is a lack of differentiated regional perspectives on eco-innovation activities of incumbents and start-ups and their development over time. A stronger focus on regional eco-innovator specialisations beyond spatial drivers and barriers is therefore necessary to enrich the literature on the geography of eco-innovation and sustainability transitions.

2.2 Research objectives: Capturing regional eco-innovation specialisations in incumbents and start-ups

Over the last two decades, researchers from diverse disciplines have shown an increased interest in the spatiality of eco-innovation emergence and its wider influence on socio-technical transitions. Conceptual and empirical studies alike have focused on various spatially constituted factors to increase the understanding of the geographical specificities and differences in eco-innovative activities towards environmental sustainability. Despite this common research interest, the different perspectives outlined above still exist largely in parallel, which is also expressed in distinctive ontological assumptions and methodological traditions. In more recent years, however, the potentials of convergence and cross-fertilisation have been recognised and calls for deeper thematic and theoretical engagement are gaining prominence (e.g., Boschma et al. 2017; Binz et al. 2020; Losacker et al. 2023).

Although studies increasingly combine conceptual approaches and seek to broaden the understanding of spatial eco-innovation activities, there is still a lack of a systematic review of the related geographical innovation and transition studies. In other words, no previous study has analysed in a comprehensive and structured way the state of research, i.e. characteristics, commonalities and differences, in order to identify overarching research gaps and complementarities between the fields of the geography of eco-innovations and sustainability transitions. So far, the existing reviews rather focus on one research stream or analytical focus at a time (Hansen and Coenen 2015; Barbieri et al. 2016; Krupoderova and Portnov 2020), but fail to acknowledge intersections between the two research directions. Hence, the first dissertation paper aims to explore the broader scholarly discourse on the geography of eco-innovations and sustainability transitions and reflect upon on potentials for future avenues towards stronger convergence. Analytically, the review draws on actors, institutions and technologies, that are fundamental to both innovation and socio-technical systems approaches (Edquist 1997; Geels 2004). Thus, the first research objective is as follows:

Research Objective 1: *Conducting a systematic literature review to ascertain geographical insights into eco-innovation activities and transformative change.*

While the growing body of research has led to a thorough understanding of the importance of geographically bound factors influencing eco-innovation development, there is still a lack of empirical insights on the relevant innovating actors. From a regional perspective, the question of *who* mainly brings about eco-innovation activities remains largely unanswered. This concerns in particular regional specificities of established and new eco-innovators. Although both are at the centre of conceptual considerations and are seen to play crucial roles in sustainable change (Hockerts and Wüstenhagen 2010; Tödtling, Trippl, and Frangenheim 2020), surprisingly little is known about how regions differ in the extent to which incumbents and start-ups contribute to eco-innovation activities. Instead, the literature is dominated on the one hand by quantitative analyses that investigate regional determinants of green start-up emergence and the greening of incumbents (e.g., Sunny and Shu 2019; Bammens and Hünermund 2023). On the other hand, there are numerous qualitative case studies that focus on the role of start-ups and incumbents in specific green industries (e.g., Hansen and Coenen 2017; MacKinnon, Dawley, Steen, et al. 2019). This dissertation, in contrast, intends in its second paper to determine regional eco-innovation activities of both incumbents and start-ups in the German transport sector and to derive a typology of regional actor specialisations. The transport sector is particularly suitable for analysis, given both its need for transformational change and strong economic importance in many regions in Germany. This leads to the second research objective:

Research Objective 2: *Analysing regional specialisations in green incumbents and green start-ups in the transport sector in Germany.*

In addition to examining how regions specialise in terms of eco-innovation activities of incumbents and start-ups, their development over time is also of strong interest. Evolutionary perspectives have gained increasing attention in the literatures on the geography of eco-innovations and sustainability transitions. Of particular concern is the emergence of specific green industries or green technologies in regions, i.e. green regional path creation, with studies predominantly drawing on qualitative case studies (Binz, Truffer, and Coenen 2016; Steen and Hansen 2018; Njøs et al. 2020; Gibbs and Jensen 2022). In this regard, previous research provides important information on relevant conditions and mechanisms for green regional development. Much less is known, however, about the long-term nature of eco-innovation development across regional contexts and beyond specific sectors. The third paper therefore seeks to capture general spatio-temporal specialisation patterns in eco-innovation activities of incumbents and start-ups. Moreover, it sets out to distinguish different regional transition trajectories, which leads to the final research objective:

Research Objective 3: *Tracing regional eco-innovation trajectories by capturing green innovative activities of incumbents and start-ups.*

3 Data and methods

In order to address the aforementioned research objectives, this dissertation makes use of quantitative and qualitative data, adopting a multi-method research approach. The first research contribution is conceptual in nature and draws on qualitative publication data to review the geographical literature on eco-innovations and sustainability transitions. The two following papers quantitatively analyse regional eco-innovation specialisations in Germany, distinguishing between established and novel actors. This ensures to capture different types of eco-innovations such as green technologies and green business model innovation, while specialisation measures, as opposed to a focus on absolute eco-innovation output, moderate typical urban-rural divides in innovation activities (e.g., Balland et al. 2020).

In a first step, research on the geography of innovative and transformative change towards environmental sustainability is analysed, contrasted and critically reflected by means of a systematic literature review. This methodological approach is particularly suitable for identifying research gaps and outlining promising future research options (Petticrew and Roberts 2006) - all the more so as the emerging field of research still appears fragmented with little interconnections between the research streams. To trace the diverse scientific knowledge production, a keyword-based search strategy in the Scopus and Web of Science (WoS) databases is applied to peer-reviewed journal articles. Sensitive searches are ensured by deriving search terms from the fields' fundamental research articles, supplemented by backward and forward citation methods (Petticrew and Roberts 2006; Barbieri et al. 2016) as well as literature graphs (Ammar et al. 2018). The quantitative count of the publication data by the two broader research directions[1] follows a comprehensive analysis along the systemic elements of actors, institutions and technologies.

Building on a central research gap identified in the literature review concerning the eco-innovation activities of established and novel actors, the second step involves an empirical analysis of regions' specialisation in green incumbents and green start-ups in the German transport sector. In general, this quantitative approach consists of both descriptive analyses of regional eco-innovator specialisations and econometric methods, i.e. logistic regression analyses, to explain the revealed spatial patterns. In this regard, a unique combination of patent and company data is used and assigned to the 96 German spatial planning regions for the period 2009-2018. Patent data mainly captures innovation activities of incumbents, usually well-established firms, and is - despite known weaknesses - a key innovation indicator in economic geography and related disciplines (e.g., Griliches 1990; Jaffe, Trajtenberg, and Henderson 1993). More precisely, all patents with the assigned Corporate Patent Classification (CPC) code Y02T in EPO's PATSTAT are selected, as these reflect climate change mitigation technologies in the transport sector.[2] For the identification of green start-ups, in contrast, the Mannheim Enterprise Panel (MUP) of the Leibniz Centre for European Economic Research (ZEW) is used. The MUP includes a variety of information on almost all German companies, including their activity descriptions, which allows to distinguish green from non-green company foundations in the transport sector. The necessary keywords are retrieved from transport-related patent classes, literature sources and other online databases.

To validate and deepen these rather static results, the third step comprises a longitudinal analysis of eco-innovation specialisations in the 401 German NUTS-3 regions from 1997 to 2018. Again, patent and company data are used to reveal regional specialisations in green incumbents and green start-ups. For this paper, however, the research interest is to analyse green regional development more generally. To do so,

[1] In an earlier version published as a working paper (Hansmeier 2021), text-analytical methods help to identify characteristic patterns of the main literature streams. This is essentially about most frequent words and key terms in the literatures.

[2] Other studies on green technology and green industrial development of regions often use the OECD ENV-TECH classification (Haščič and Migotto 2015), which goes beyond the CPC classification in some technological domains, but is similar for the transport sector.

green patents are retrieved from OECD's REGPAT database using the ENV-TECH classification (Haščič and Migotto 2015). Green start-ups, on the other hand, are extracted from ZEW's MUP database using a keyword-based search strategy developed by Rammer et al. (2023). Methodologically, this work pioneers the application of social sequence analysis (SSA) approaches in economic geography, which are commonly used in the social sciences (e.g., Abbott and Tsay 2000; Gauthier, Bühlmann, and Blanchard 2014). SSA methods offer the advantage of tracing and comparing the long-term development of individual units such as regions or countries. It is therefore surprising that this set of methods has not yet received wider attention in geographical innovation and transition studies. In this case, SSA allow to determine how regional eco-innovation trajectories evolve over time, capturing both region-specific and cross-sectional characteristics in eco-innovation specialisations. Finally, optimal matching techniques and clustering methods (e.g., Abbott 1995) are used to identify similar types of regional eco-innovation trajectories that are characterised using socioeconomic data at the regional level.

4 Overview of research contributions

Before presenting the articles that constitute this dissertation, the following section discusses related research contributions that I have been involved in over the past few years. These studies - including peer-reviewed publications, working papers and book contributions - are not part of the dissertation itself. However, they deserve a brief explanation as they shed light on complementary aspects that have significantly influenced and enriched the research in this dissertation.

4.1 Related research

During the process of determining this dissertation's research subject, Katharina Schiller, Karoline Rogge and I conducted a literature review on methodological diversity in transition studies (Hansmeier, Schiller, and Rogge 2021). For this purpose, we systematically assessed studies dealing with socio-technical transitions published in key journals of the scientific field from 2016 to 2019. Although transitions research has developed very dynamically in recent years, our findings suggest that the methodological diversity remains somewhat limited. This is particularly true with regard to research methods and data sources, as qualitative research approaches based on documents and interviews still predominate. In addition to new and alternative research methods, we propose a more critical examination of the theoretical concepts and a diversification in terms of sectoral and geographical coverage. The latter also includes a detailed consideration of (global) transition dynamics and their interactions with the regional level.

Following on from recent debates in innovation studies and transitions research, Sebastian Losacker and I call for a stronger combination of supply and demand side eco-innovation policies at the regional level (Hansmeier and Losacker 2021). So far, the literature on green regional (path) development focuses mainly on policies that aim at the emergence of eco-innovations, while the transitions literature usually emphasises their diffusion across regions. Referring to the regional lead market concept (Losacker and Liefner 2020), we emphasise that the alignment of regional supply and demand policies could be both environmentally and economically beneficial if incentives are created for regions to drive eco-innovation diffusion. Demand-side eco-innovation policies are thus complementary to existing approaches that usually target the production side.

Another article on the regional dimension of eco-innovations was compiled in collaboration with Sebastian Losacker, Ingo Liefner and Jens Horbach. Our contribution - published both as a preprint and peer-reviewed publication - (Losacker et al. 2021; 2023) critically reviews the geographical literature on eco-innovations' regional determinants and outlines an agenda for future research. The results indicate that previous studies primarily focus on supply-side determinants such as technological relatedness and actor collaborations. Drawing on several limitations and blind spots in the literature, we provide arguments how future research would profit from a stronger focus on technological and institutional contexts as well as demand-side conditions.

While the aforementioned articles focus more generally on transitions and innovation research and related policy implications, my colleagues at Fraunhofer ISI and I have also been working more intensively on the so far underexplored relationship between structural change and sustainability transitions at the regional level. Together with Thomas Stahlecker and Knut Koschatzky, I discuss funding approaches in the context of innovation-based structural change at the regional level in Germany (Stahlecker, Hansmeier, and Koschatzky 2021). We argue that promising innovation policies and governance approaches have recently emerged that not only address regional structural change, but can also enhance socio-technical transitions on a broader scale. These range from the support of regional participation and strategy processes to the possibility of promoting innovation through the targeted modification of regulatory framework conditions. (De-)regulation appears to be particularly relevant because it enables experimental developments to be tested under real-world conditions. This approach provides direct links to transitions research, which also emphasises the importance of local niche experimentation for novel, potentially more sustainable solutions.

As indicated before and also systematically analysed in more detail in the first dissertation paper (cf. section 5), research on the geography of eco-innovation and sustainability transitions are not yet well aligned. Remarkably, central concepts from economic geography have hardly been applied in transition studies so far. Against this background, Knut Koschatzky, Andrea Zenker, Thomas Stahlecker and I propose that a broader understanding of regional innovation systems (RIS) is helpful in analysing socio-technical change from a small-scale perspective (Hansmeier et al. 2022). In particular, we stress the importance of actors outside the triple helix of science, business and politics, as well as the integrated view of innovation supply and demand, which represent promising conceptual cross-references between the research streams.

Moreover, as part of an accompanying research of the BMBF (*Federal Ministry of Education and Research, Germany*) funding programme "WIR!”, Knut Koschatzky, Esther Schnabl, Thomas Stahlecker, Florian Wittmann, Andrea Zenker and I discuss implications of both structural weakness and socio-technical transitions in regions (Koschatzky et al. 2022). On the basis of theoretical concepts and an analysis of empirical studies, we identify facilitating and hindering determinants and derive possibilities for lagging regions to adapt. The enabling of local experimentation and strengthening of regional initiatives, either by the regions themselves or through policy action at national and international level, are seen as particularly important regional policy approaches. In an adapted version of this paper (Koschatzky et al. 2023), we pay particular attention to the small-wins strategy. This recently proposed governance approach (Bours, Wanzenböck, and Frenken 2022) aims to involve and support bottom-up initiatives, thus providing additional transformative policy stimulus for regions to address grand societal challenges.

Following on from the conceptual arguments made in the papers before, Knut Koschatzky and I then undertook a more empirically grounded analysis of structural and systemic change (Koschatzky and Hansmeier 2023). More specifically, we aimed at analysing how regions that are particularly affected by economic, social and demographic challenges, i.e. structurally weak regions, deal with grand societal challenges (e.g., the climate or energy crisis) and which policy instruments can be useful to align processes of structural and transformative change. For this purpose, we conducted - together with the help of the Fraunhofer ISI project team - about 20-30 semi-structured interviews with actors and stakeholders from those regions funded in the "WIR!" implementation phase. The interviews reveal that the regional alliances mainly set innovative impulses for changes of industrial or technological paths and are predominantly concerned about topics such as qualification and shortage of skilled workers. In contrast, strategic regional action is hardly ever observed when it comes to the initiation of transformational processes to cope with global (environmental) challenges. Although the project funding is aimed to a lesser extent at system-changing activities, it is clear that regions need other or complementary funding in this respect. This is also due to the fact that existing political support targets the regions' internal actor and knowledge bases and less the generation of sustainability-oriented solutions that require changes in broader institutional settings.

4.2 Research articles constituting the dissertation

Overall, this dissertation consists of three interrelated research contributions. Table 1 summarises the essential information on individual articles that are all under review in peer-reviewed journals (as of August 2023). In addition, two of the three articles have already been published as preprints.

Table 1: Overview on this dissertation's research articles

No.	Title & Authors	Objectives	Methods & Data	Status & Journal
1.	The geography of eco-innovations and sustainability transitions: A systematic literature review *Hansmeier, H., Kroll, H.*	To review and compare the literatures on the geography of eco-innovations and sustainability transitions	Systematic literature review Publication data	Under review *ZFW – Advances in Economic Geography* Note: An earlier version of this paper has been published in the *Geography of innovation and sustainability transitions (GEIST) working paper series* (Hansmeier 2021)
2.	Incumbents and Start-ups as Eco-Innovators in Different Types of Regions: Insights from the Transport Sector in Germany *Hansmeier, H., Losacker, S., Bersch, J., Kroll, H.*	To identify and explain regional specialisations in eco-innovation actors in the transport sector in Germany	Descriptive statistics and logistic regression models Company and patent data	Under review *Regional Studies*
3.	Regional eco-innovation trajectories *Hansmeier, H., Losacker, S.*	To trace, contrast and characterise long-term eco-innovation trajectories of German NUTS-3 regions	Sequence analysis methods, cluster analyses, optimal matching techniques and descriptive statistics Company and patent data	Under review *European Planning Studies* Note: A slightly modified version of this paper is available as a preprint in *Papers in Evolutionary Economic Geography* (Hansmeier and Losacker 2023)

Given that eco-innovation is a necessary condition for the shift towards a green economy and more sustainable socio-technical systems (Kemp et al. 2019), it is surprising that geographical research on these topics somewhat co-evolved over the past years and is therefore still fragmented. Against this background, the first article of the dissertation aims to compare and contrast research work in the context of the geography of eco-innovations and sustainability transitions through a systematic literature review along the analytical categories of actors, institutions and technologies (incl. knowledge and material artefacts). Together with Henning Kroll, who assisted me in drafting and revising the paper as well as co-authoring the research agenda, we reveal differences in analytical emphases of the literatures that go beyond epistemological and methodological particularities. The work focussing on eco-innovation mainly considers actors as facilitators of innovative change and green development, their regional embeddedness in socio-institutional structures and the resulting path and place specificity of industrial and technological developments. In contrast, research which relates to the geography of sustainability transitions usually embraces a sectoral perspective, stressing the relational and multi-scalar nature of socio-technical change. Transitions are seen as spatially constituted, enabled or hindered by a wide range of actor networks and institutional aspects. We argue that mutual inspiration between these two broader research directions is necessary and beneficial in gaining a more nuanced and complementary picture of the spatiality of innovation-based sustainable change. Against this background, we highlight promising future avenues towards stronger convergence.

The actor perspective raised before is the basis of this dissertation's second article, in which we expand the conceptual discussion of the literature review with empirical analyses. The article benefited substantially from the co-authorship of Sebastian Losacker (help with empirical modelling as well as description and discussion of findings), Johannes Bersch (help with data provision and preparation) and Henning Kroll (discussion of interim results and writing parts of the text). In essence, we investigate regional specialisations in eco-innovation actors - comparing incumbents with start-ups - and ask whether and to what extent the actor prevalence differ between regions. Using regional patent and company data for the German transport sector, we derive a regional typology that reflects the regional heterogeneity in eco-innovation actor specialisations. In addition, we control for regional characteristics that help to explain these spatial differences in eco-innovation actor specialisations. Many regions seem to specialise in either incumbents or start-ups and some regions qualify as hotspots, i.e. with an above-average presence of both types of actors. Other regions show no specialisation at all. The endowment with human capital, measured as the share of high qualified people in a region, proves to be a key determinant of regional differences in the relative importance of eco-innovation activities.

Finally, article three sets out to investigate the extent to which the aforementioned patterns of regions' eco-innovation specialisations apply beyond individual sectors and how green regional development unfolds over a longer period of time. To this end, Sebastian Losacker - who assisted with conceptualisation, empirics and results analysis - and I apply sequence analysis approaches. Although this set of methods is particularly suitable for tracing and comparing the development of individual units such as countries or regions, it has not yet received attention in economic geography. Drawing on unique green incumbent and green start-up data for the 401 German NUTS-3 regions over the period 1997-2018, we reveal that regions seem to primarily follow persistent trajectories of eco-innovation specialisations, with neighbouring regions exhibiting similar patterns. That is, the majority of regions display either no specialisation, a dominance of just one actor, or the simultaneous strong presence of green incumbents and green start-ups. Only a smaller share of regions is able to develop above-average eco-innovation activities over time, driven by both types of actors. Remarkably, this greening originates from the previous specialisation of the respective other type of actor. In essence, our results suggest that green regional development is highly path-dependent and rather gradual, highlighting essential insights for scholarly and policy debates on systemic change towards environmental sustainability.

PART TWO: RESEARCH ARTICLES

5 The geography of eco-innovations and sustainability transitions: A systematic literature review

Authors: Hendrik Hansmeier, Henning Kroll

Status: Under Review in *ZFW – Advances in Economic Geography* (as of August 2023)

Abstract

The need to address environmental challenges such as climate change or resource depletion is more urgent than ever. However, the spatial dimension of pathways towards sustainability has only attracted scholarly interest over the last decade. Based on a systematic review, this article aims to identify both commonalities and differences in the existing geographical literature, which oscillates between a focus on the development of eco-innovations on the one hand and socio-technical transitions on the other. This is not only due to different disciplinary backgrounds, but also to deliberately different emphases on the basic systemic elements of actors, institutions and technologies. Despite their common object of interest, the review shows that different contributions maintain diverse perspectives on sustainability dynamics and the overall field of research remains fragmented. Nonetheless, the nuanced synthesis of research findings allows us to identify complementarities that constitute promising avenues for future geographical research

5.1 Introduction

The development and diffusion of innovations aimed at reducing environmental burdens are essential to make socio-technical systems more sustainable (Smith, Voß, and Grin 2010; Boons and McMeekin 2019). Against this background, scientific research has come to increasingly address issues around desirable, i.e. sustainability-focused, innovation (Rennings 2000; Barbieri et al. 2016) and systemic transitions (Markard, Raven, and Truffer 2012; Köhler et al. 2019). In the political sphere, this *"orientation towards [a] directionality of innovation"* (Edler and Boon 2018, 433) has led to initial steps towards a paradigm shift, where transformative innovation policies complemented the prevailing focus on economic growth and competitiveness (Weber and Rohracher 2012; Schot and Steinmueller 2018).

During the early years of this normative turn in innovation studies and innovation policy (Sjøtun and Njøs 2019; Uyarra, Ribeiro, and Dale-Clough 2019), the spatial dimension of innovation-based and transformative change has remained largely unaddressed. Recently, however, a number of conceptual and empirical studies have started to provide useful insights on spatial conditions, their interdependencies and the resulting geographical unevenness of environmental sustainability (Cooke 2011; Gibbs and O'Neill 2014; Boschma et al. 2017; Strambach 2017; Grillitsch and Hansen 2019).

In general terms, geographical research efforts essentially evolve around two related and intertwined perspectives. On the one hand, a perspective that emphasises the potential of environmentally oriented innovations, i.e. eco-innovations, and their enabling factors (e.g., Cainelli, Mazzanti, and Montresor 2012; Costantini, Mazzanti, and Montini 2013; Perruchas, Consoli, and Barbieri 2020). On the other hand, a perspective that highlights the need for systemic sustainability transitions (e.g., Coenen, Benneworth, and Truffer 2012; Truffer, Murphy, and Raven 2015; Binz et al. 2020). Due to this in a way fundamental differences, the two perspectives do not integrate naturally and the attempt at such integration was initially present in fewer contributions - although its potential must appear obvious. More recently, however, research attempts have been undertaken towards that end, such as work on green industrial and technological path development in regions (Grillitsch and Hansen 2019; Trippl et al. 2020), the green economy and green growth (Gibbs and O'Neill 2014; Capasso et al. 2019) or (regional) lead markets (Quitzow, Walz, and Köhler 2014;

Losacker and Liefner 2020). As we will argue, the different methodological and ontological features of the two sides of the discourse do not imply that they are fundamentally irreconcilable. By means of example, many insights of the innovation systems literature still hold despite the now evident need for transformative change and remain instrumental in understanding the process of developing disruptive ideas and innovations.

Although the geographical literature concerned with sustainability transitions does not deny that eco-innovations and their enablers are central part of transition dynamics, it focuses on co-evolving institutional arrangements, which can be both obstacles and facilitators of socio-technical change. With a view to its perspectives on space, research on the geography of transitions follows relational and constructivist approaches of social and economic processes that it conceives as driven by multi-scalar relations of actor dynamics (Zolfagharian et al. 2019; Binz et al. 2020; Miörner and Binz 2021). Moreover, transition studies conceptually construct sectoral change and mainly uses qualitative case studies to uncover relevant factors that enhance or impede transitions towards sustainability (Hansen and Coenen 2015; Mattes, Huber, and Koehrsen 2015; Strambach and Pflitsch 2020). This literature is therefore interested in the processes after a potentially environmentally friendly solution is implemented, i.e. it mainly looks at the application and demand side of innovations as well as their diffusion across space (van den Berge, Weterings, and Alkemade 2019).

The geographical discourse on eco-innovations is empirically and conceptually more heterogeneous but united by the fact that it finds its origin in innovation economics. As such, it regularly takes a more resource- and (growth) potential-oriented perspective and conceives institutions as enabling factors rather than as an element of inhibiting regimes. Such research on the geography of eco-innovations usually tends to quantitatively assess spatial determinants of green innovations, considering them a key prerequisite of technological and industrial change towards sustainability (Cooke 2012; Cainelli, D'Amato, and Mazzanti 2015; Perruchas, Consoli, and Barbieri 2020). Put differently, much of this literature starts from a territorial supply-side perspective on technological and industrial development and, in doing so, tends to maintain a more traditional concept of space as composed of political reference areas in which relevant institutions are constituted and resources made available. Importantly, this explicitly includes the discourse emerging in continuation of the (regional) innovation systems literature. However, it often lacks explicit conceptual references to broader sectoral changes, whose occurrence it documents (Horbach 2014; Antonioli, Borghesi, and Mazzanti 2016; Krupoderova and Portnov 2020).

Despite the abovementioned differences in research objects, methods and concepts, research on the geography of eco-innovations on the one hand and sustainability transformations on the other hand do not represent opposing poles. Rather, both directions of research, and the various research streams in between oscillating between them, agree on the systemic character of eco-innovative or transformational processes, constituted by (networks of) actors, institutions and material artefacts/knowledge (i.e. technologies) (Markard, Raven, and Truffer 2012; Dawley 2014; Rohe and Chlebna 2021).

Put differently, the comprehensiveness and pertinence of each research direction is reflected in the degree to which spatial dynamics along the institutional, actor-oriented and technological elements are addressed. Against this background, it seems timely to systematically compare and analyse the last decade's rich literature on the geography of eco-innovations and sustainability transitions (Hansen and Coenen 2015; Krupoderova and Portnov 2020). By classifying current papers based on keywords characteristic for either initial stream of literature, this paper aims to identify persistent differences in perspective as well as overlaps and complementarities that hint at emerging convergence. In deriving integrative research possibilities, we follow the call of Binz et al. (2020, 3), who commented on the role of geography in the transitions research agenda and see "the need to combine the topical concerns [...] with a more serious engagement with current theorizing in human geography and related spatial theories in the social sciences".

The structure of the paper is as follows. After characterising conceptual and theoretical features of geographical work on eco-innovations and sustainability transitions, the methodology applied to conduct a systematic literature review is outlined in detail. Subsequently, the results sections shed light on similarities, differences and complementarities between the two research streams regarding their conceptual perspectives on institutions, technologies and actors. Finally, we document the necessity to further reconcile innovation- and transformation-oriented perspectives in order to better understand spatial dynamics against the backdrop of grand societal challenges.

5.2 A first overview: geographical work on eco-innovations and sustainability transitions

Not least since a "spatial turn" in eco-innovation oriented and transitions research has emerged, the "inattention to space" (Gibbs and O'Neill 2014, 212) is increasingly being challenged, paving the way for necessary geographic debates (Coenen, Hansen, and Rekers 2015; Rinkinen, Oikarinen, and Melkas 2016). Specifically, it has been recognised that eco-innovation and transformation processes, as well as their heterogeneity and disparity (Coenen, Benneworth, and Truffer 2012), imperatively requires an inclusion and understanding of the spatial context. Surprisingly, however, the existing geographical literature remains quite heterogeneous, although eco-innovations, which include (non-)technological measures that lead to a reduction of environmentally harmful impacts, are considered a necessary condition for systemic transformations (Rennings 2000; Kemp et al. 2019). Accordingly, it appears timely to review the relevant literature with the double ambition to which extent such a bifurcation still exists and where first signs of structural overlap and integration become visible. Subsequently, a more detailed inquiry will explore which particular aspects of either side can contribute to the geographic debate and which further insights may result from their more integrated discourse in the future.

5.2.1 The geography of eco-innovations

The diverse research on the geography of eco-innovations recognises that the generation and adoption of eco-innovations varies across places, due to spatially distinct supply and demand side characteristics as well as regulatory support and institutional structures (Horbach 2014; Perruchas, Consoli, and Barbieri 2020). Far from forming a clearly delimited field, related research encompasses spatial perspectives on green technology and industry development (e.g., Barbieri, Perruchas, and Consoli 2020; Perruchas, Consoli, and Barbieri 2020) as well as the identification of regionally specific determinants for eco-innovations and green entrepreneurship (e.g., Horbach and Rammer 2018; DiVito and Ingen-Housz 2019). In essence, the research's overarching interest is to examine region- or country-specific conditions that enable a wide variety of innovation activities conducive to green development (Cooke 2012; Antonioli, Borghesi, and Mazzanti 2016; Mazzanti 2018).

Although eco-innovations can be explicitly technological, organisational, social or institutional in nature (Rennings 2000), research on this topic is strongly influenced by the literature on economics of innovation and technological change. Particularly influential in this regard is the field of evolutionary economics (Boons and McMeekin 2019; Barbieri, Marzucchi, and Rizzo 2020). Its basic assumptions are that technological change and innovative activities are primarily shaped by organisational routines, i.e. regular and predictable business behaviour with persistent and heritable features (Nelson and Winter 1982). Hence, historical trajectories of economic development are likely to result in spatially uneven innovation activities. These general findings form the basis of evolutionary approaches within economic geography (Boschma and Frenken 2011). In parallel, the relationship between economic development and environmental problem solution associated with eco-innovations originated from ecological modernisation theory (Spaargaren and Mol 1992; Boons and McMeekin 2019). Accordingly, technological change has to be guided by environmental policy and regulation to enhance both economic competitiveness and sustainable development (Gibbs 2000).

Today, much of the established literature around environmentally related innovation and change relies on quantitative research methods. These studies primarily use large samples of patent, publication, firm-level and/or socio-economic data obtained from official administrative databases or surveys to investigate the distribution of eco-innovative activities across regions or countries (Horbach, Chen, and Vögele 2014; Santoalha and Boschma 2021). Accordingly, eco-innovation activities and their interrelationships are typically investigated at the level of clearly definable spatial units (Hansen and Coenen 2015), with a predominant focus remaining on resource endowments and socio-institutional framework conditions that characterise specific regions. Against this backdrop, empirical analyses draw on administrative territories that have a certain degree of political capacity and policy making (Cooke, Uranga, and Etxebarria 1997), such as districts, federal states or countries (e.g., Corradini 2019; Barbieri, Perruchas, and Consoli 2020).

Conceptually, research on eco-innovations and its spatial characteristics builds on established notions from innovation studies in economic geography that have been widely applied in recent decades. These include, for example, (regional) innovation systems and evolutionary approaches such as spatial path dependency and regional branching (Dawley 2014; Perruchas, Consoli, and Barbieri 2020). Both emphasise the importance of geographical proximity for knowledge spillovers and interactive learning processes, some of which stem from traditional approaches towards establishing innovation capacities of territories (Jaffe, Trajtenberg, and Henderson 1993; Boschma 2005). Hence, most of the studies draw on theories that are at least developed from a basis in traditional economics although their approach has been substantially broadened and does not necessarily take a neo-classical stance (see Table 2 for summary).

5.2.2 The geography of sustainability transitions

Spatial perspectives have more recently also been given greater attention in transition studies (e.g., Truffer, Murphy, and Raven 2015; Boschma et al. 2017) which is also evidenced by the geography's addition to the STRN research agenda (Köhler et al. 2019; Binz et al. 2020). Different from the economically informed eco-innovation studies discussed above, this literature takes a decidedly multidisciplinary perspective. Beyond insights from economics and sociology, it is substantially informed by political science, historical insights, technological perspectives from the domain of engineering and discourse-oriented ones from psychology and the humanities (Zolfagharian et al. 2019).

More precisely, sustainability transitions research has its origins in the sociology oriented science and technology studies (STS). With the technology turn in STS during the 1980s, the field started to embrace core perspectives from innovation studies like evolutionary approaches of technological change and innovation (Boons and McMeekin 2019). The disciplinary crossover was enriched by ideas of ecological modernisation (Spaargaren and Mol 1992), which call for adapted (economic) behaviours to reduce environmental damages (Hansen and Coenen 2015; Boons and McMeekin 2019). In this regard, early research on sustainability transitions focused primarily on the role of technologies (Kemp and Soete 1992). Acknowledging the interdependencies of actors, institutions and technologies within sustainability dynamics, however, the notion of socio-technical systems has become increasingly central (Kemp, Schot, and Hoogma 1998; Markard, Raven, and Truffer 2012).

With a view to geographies, the transitions literature emphasised that transitions towards sustainability result from complex, socially constructed processes. Beyond economic activities, the actors' narratives, stories, perceptions and interpretations are essential for the generation of transformational knowledge (Zolfagharian et al. 2019).

By invoking a multi-level perspective, it emphasises that actor coalitions can be agents of change as well as of obstruction and continuity (Steen 2016; Sjøtun 2020) To uncover these conflictual transition dynamics, most empirical studies use case studies that explain their spatial unevenness, systemic interdependencies and spatially distinct patterns (e.g., Martin 2020; Strambach and Pflitsch 2020). However, methodological challenges arise on how to gain generalisable insights on the complex and multi-scalar geography of sustainability transitions (Hansen and Coenen 2015). To address this shortcoming, some recent empirical contributions have, in addition, begun to draw on quantitative comparative analyses (Meelen, Frenken, and Hobrink 2019) or social network analyses (Binz, Truffer, and Coenen 2014; Fontes, Sousa, and Ferreira 2016).

As the consideration of space remains comparatively new to the STS debate, most studies still seek to develop clearer conceptual notions, doing so, in their overt majority, from a relational perspective. In order to increase context and space sensitivity, much of the previous research on the geography of sustainability transitions has contributed to adjust or reframe the - initially a-spatial - transition frameworks, especially the multi-level perspective (MLP) and technological innovation system approach (TIS) (Lawhon and Murphy 2012; Bergek et al. 2015; Coenen 2015). Although initially setting system boundaries at the national level (Coenen 2015; Wieczorek et al. 2015), geographical studies increasingly acknowledge that TIS as well as sectoral niche and regime structures emphasised in MLP, are characterised by local variations and globally interconnected transition dynamics (Dewald and Fromhold-Eisebith 2015; Boschma et al. 2017). These findings led on the one hand to the elaboration of frameworks that stress the spatially interrelated character of innovation processes such as the (regionalised) global innovation systems (GIS) framework (Binz, Truffer, and Coenen 2016; Rohe 2020) or global socio-technical regimes (Fuenfschilling and Binz 2018). Against the background of both global production and multi-scalar actor networks as well as the territorial embeddedness of social and institutional dynamics, work on local/global niche development and the influence of experimentation emerged in the last years (Coenen, Raven, and Verbong 2010; Sengers and Raven 2015; Roesler and Hassler 2019) (see Table 2 for summary).

Table 2: Features of geographical work on eco-innovations and sustainability transitions

Geographical research oriented towards …	Research focus	Origins	Understanding of geography	Methodological approaches	Concepts and frameworks
… eco-innovations	• Territory-specific determinants for the emergence of eco-innovations	• Evolutionary economics of technological change • Institutional economics • Ecological modernisation	• Regions and countries as empirical items • Cleary delineated spatial units	• Mostly quantitative research methods • Comparative analyses and generalisable knowledge	• Territorial innovation systems • Regional branching • Regional path development
… sustainability transitions	• Place-specificity and multi-scalarity of sustainability transitions	• Science and technology studies (STS) • Ecological modernisation	• Regions and countries as objects of conceptual consideration • Relational approaches • Place, space and scale are socially constructed	• Mostly qualitative case studies • Stressing particularities of distinct places	• (Contextual) technological innovation systems • local/global niche development and experimentation • Global socio-technical regimes

5.3 Identification of literature for in-depth review

The rationale for further reviewing the literature on the geography of eco-innovations and sustainability transitions in-depth, is to provide better and clearer insights into these related strands of research. To this end, we will first examine whether the abovementioned premise of a diverse strand of literature oscillating between two converging yet still clearly distinguishable poles or perspectives can be substantiated in practice.

Although this in-depth review represents a structured, transparent and replicable procedure, we are aware of the limitations of this methodical procedure. In essence, information retrieval is strongly dependent on the search strategy, which is influenced to a certain extent by the researchers' scientific background. The same applies to the assessment of the relevance and analysis of the obtained literature. In addition, differences in language and publication types, for example, can lead to some relevant contributions not being included in the analysis (Tranfield, Denyer, and Smart 2003; Snyder 2019). To minimise a biased selection and analysis, the literature review therefore follows in principle the systematic approach illustrated in Figure 1 (see also Petticrew and Roberts (2006)).

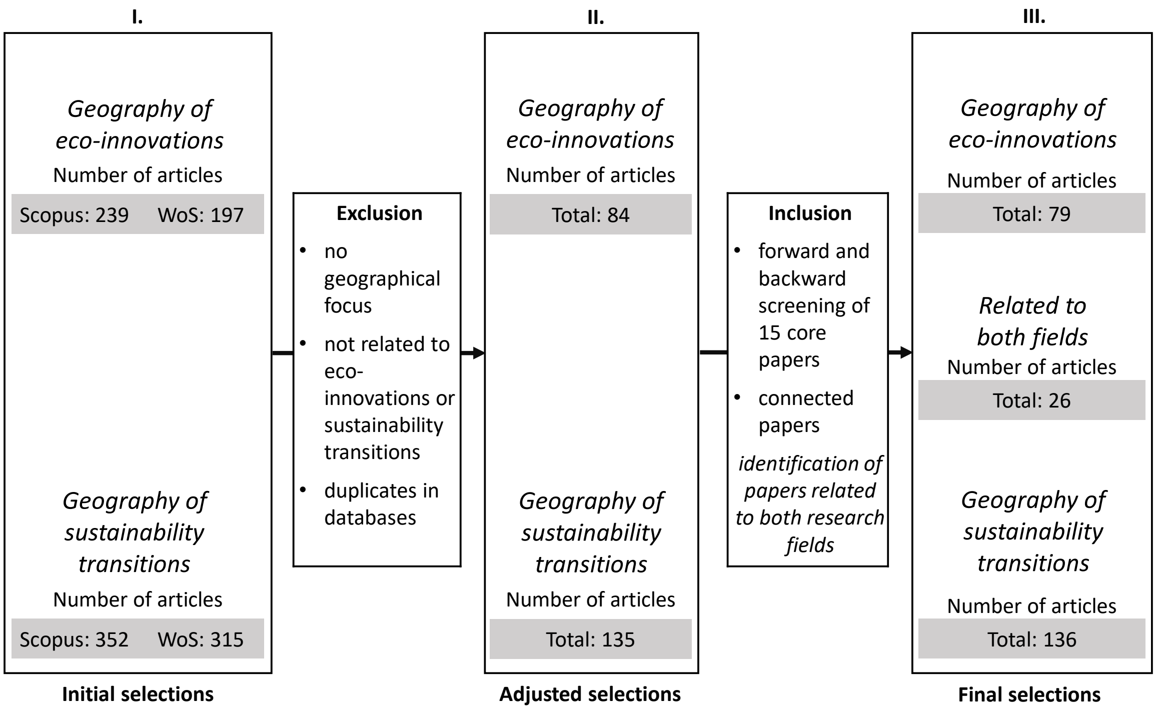

Figure 1: Procedure for identifying the relevant literature (author's own figure based on Kivimaa et al. (2019))

To identify the relevant corpora of literature related to both directions of research separately, the systematic review started by defining characteristic keywords that refer to either eco-innovation and transitions research and include geographical/spatial terms. As such, both search queries consist of two parts (see Table A 1 in Appendix A). More precisely, the assumed core characteristic of a suggested stream of eco-innovation literature are translated into keywords around the central notions of "innovation" and "development" that reflect this literature's assumed focus on innovation as such and economic development as a core objective. For this purpose, the search terms, including frequent synonyms for eco-innovation, were gathered from the seminal paper by Rennings (2000) and the review by Barbieri et al. (2016). Additionally, notions like "branching" or "entrepreneurship" denote specific, long standing strands of literature that we have - by means of assumption - attributed to this broader field.

Conversely, the known core characteristic of the emerging geography of transitions literature is reflected in the core notions of "transition" and "socio-technical change" as well as a number of others characteristic for the field, like "technological innovation system” or “multi-level perspective”. These were drawn from reviews by Markard, Raven, and Truffer (2012), Kivimaa et al. (2019) and Hansmeier, Schiller, and Rogge (2021). Quite naturally, this lead to a more precisely delineated field of studies than in the case of eco-innovation that cannot to the same extent take recourse to a specific set of vocabulary. That, however, is not necessarily at odds with the core ambition of this paper: to establish whether - at all - there are indeed still two main strands of literature that can be considered as distinct.

To avoid the inclusion of non-geographical literature, both search strategies are complemented with a concise yet comprehensive list of geography-specific terms such as “spatial”, “local”, “regional” and “international” which serve as a necessary condition for any paper to be included in the corpus of reference for this study (Boschma et al. 2017; Binz et al. 2020; Krupoderova and Portnov 2020).

Using combinations of these terms, titles, abstracts and keywords of documents listed in both the Scopus and Web of Science (WoS) databases were sourced. Since document types such as books, conference proceedings and reports are underrepresented in Scopus and WoS (Mongeon and Paul-Hus 2016), the search only included peer-reviewed journal articles. As of June 23, 2021, a total of four search strings – two databases, two broader directions of research – were performed. These initial selections comprised 239 Scopus-listed articles (WoS: 197) related to the geography of eco-innovation and 352 Scopus-listed articles (WoS: 315) related to the geography of sustainability transitions.

The next step involved the exclusion of irrelevant work leading to adjusted selections. By screening the abstracts - or, in case of ambiguity, the entire study - those articles were excluded that had neither a distinct geographical focus, nor a connection to the broader eco-innovations or sustainability transitions research fields respectively[3]. The exclusion of duplicates reduced the preliminary number of studies by 84 and 135 respectively (see Figure 1).

Due to the literatures’ heterogeneity, not all relevant studies could be identified with the initial search queries. Following the approach of Kivimaa et al. (2019), further articles were searched by using forward and backward citations. As this step builds on

[3] These include, for example, studies on urban planning and urban sustainability, political and educational transitions as well as literature on green and post growth without references to eco-innovations/transitions.

established work (Petticrew and Roberts 2006), the focus was on the 15 most cited articles in each field. As a second search strategy, the "connected papers" visual tool[4] was used, which draws on the literature graph of Ammar et al. (2018) and identifies papers that are strongly connected to a given paper. Unlike building a citation tree, the algorithm uses co-citation and bibliographic coupling, thus clustering similar papers together. This approach was again applied for the 15 most cited papers of each field. The final selection for the research on the geography of eco-innovations comprises a total of 79 journal articles, and that for research on the geography of sustainability transitions to 136 journal articles. 26 papers can be assigned to both strands of literature (see also Table A 2 in Appendix A for overview of the articles).

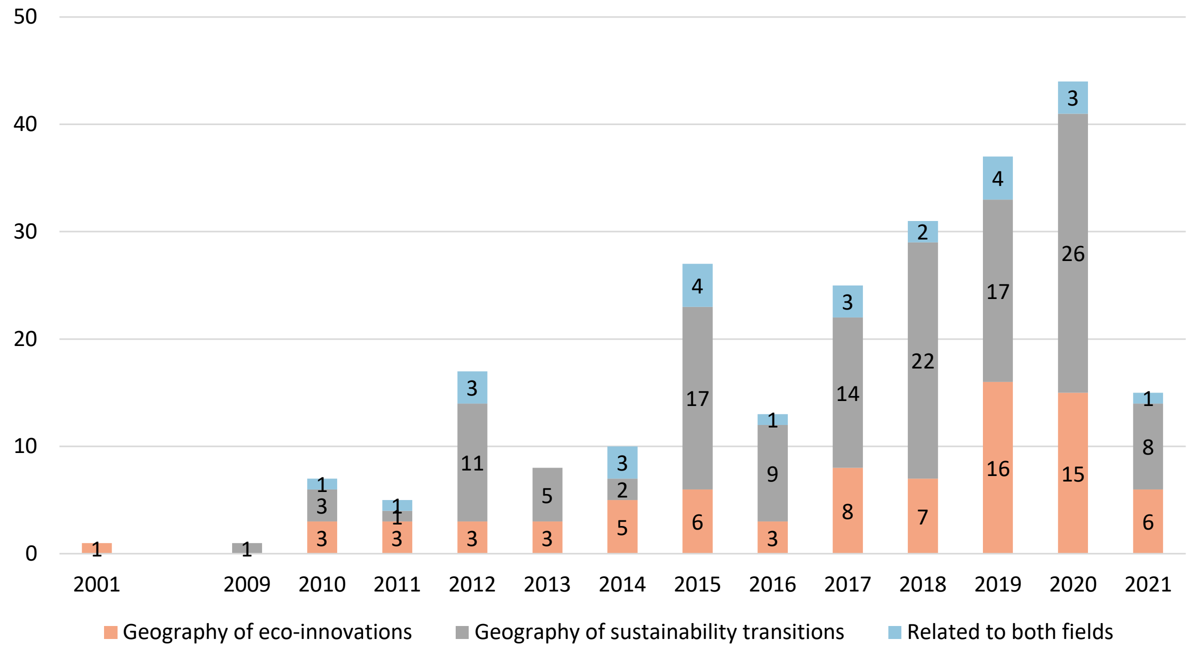

Figure 2: Number of articles published by year and research stream

When looking at the development over time (see Figure 2), it becomes apparent that both lines of research started to emerge in the late 2000s. While the years after 2009 were shaped by a rather moderate development, the annual publication output for the geographical literature on eco-innovation has risen sharply since 2017. A very similar dynamic is also evident in the literature on the geography of sustainability transitions, in line with the overall development of transition studies (Köhler et al. 2019; Hansmeier, Schiller, and Rogge 2021). More importantly, the analysis confirms our

[4] www.connectedpapers.com

initial hypotheses that much journal articles can only be assigned to one of the two perspectives, despite a rather broad search strategy.

5.4 Geographical perspectives on key elements influencing innovative and transformative change towards sustainability

Considering that spatial conditions have a crucial impact on eco-innovation and the transition to a green economy and sustainability in general (Horbach 2014; Boschma et al. 2017; Binz et al. 2020), some previous work has already reviewed the relevant geographical literature. However, these reviews only address either the geographical literature on eco-innovation (Krupoderova and Portnov 2020), innovation in the context of green growth (Capasso et al. 2019) or sustainability transitions (Hansen and Coenen 2015). Since our text-based analysis has corroborated the existence of two still noticeably distinct directions of geographical literature on eco-innovative and transformative change, the following sections will explore in more detail whether our initial priors on these streams characteristics actually apply, and, if so, to what degree and in what ways.

Unlike Capasso et al. (2019) and Hansen and Coenen (2015), for example, who emphasise similar factors around policies, institutions, technological capabilities, markets or physical resources, we assume differences in perspective with regard to key systemic elements of institutions, actors and technologies. There are two main reasons for this. On the one hand, the aforementioned categories partly overlap, for example, policies may well be considered formal institutions (Capasso et al. 2019). On the other hand, the categories on actors, institutional and technological elements help to explain the spatial development dynamics of systemic change towards sustainability without explicitly referring to individual actions (micro-level perspective) or developments at the macro-level such as political or economic systems (Köhler et al. 2019).

5.4.1 Actors

Usually understood and conceptualised as organisations (Rohe and Chlebna 2021), actors are crucial in generating knowledge and shaping power within networks that drive eco-innovations, green technologies and sustainability transitions (Wieczorek 2018; Tödtling, Trippl, and Frangenheim 2020). The diverse research perspectives agree that these actor networks are to a significant extent constituted locally or regionally, as geographical proximity facilitates diffusion processes and relations between actors (Gibbs and O'Neill 2014; Hansen and Coenen 2015).

With its perspective more strongly grounded in regional economies, a large part of the established geographical literature on eco-innovation tends to primarily consider dynamics and enabling conditions within specific regions (Cooke 2011; Antonioli, Borghesi, and Mazzanti 2016; DiVito and Ingen-Housz 2019). While an acknowledgment of the role of multi-national companies and transnational entrepreneurs is increasingly present (Cainelli, Mazzanti, and Montresor 2012; Chiarvesio, De Marchi, and Maria 2015), it does not commonly occupy centre stage. Research on the geography of transitions, in contrast, which is based primarily on a relational understanding space (Raven, Schot, and Berkhout 2012), tends to emphasise that actor networks might quite commonly transcend spatial scales (Jiusto and McCauley 2010; Coenen 2015). Therefore, a multitude of actors – both inside and outside the specific territory under study - is potentially relevant to shape processes of eco-innovative and transformative change (Truffer and Coenen 2012; Wieczorek 2018) (see Table 3).

Based on a perspective drawing on evolutionary and institutional economics, moreover, the geographical literature on eco-innovation, sees actors mostly as drivers and facilitators of (socio-)economic activity. They perform research, invent, innovate, produce, enact legislation or whatever precisely to enable green technological change, create value and advance the development of society both economically and environmentally (e.g., Cooke 2010; Antonioli, Borghesi, and Mazzanti 2016). So far, a remarkable share of this research strand focuses primarily on actors from academia, politics and business, the so called "triple helix", with particular emphasis on the role of established companies and start-ups (Georgeson, Caprotti, and Bailey 2014; Colombelli and Quatraro 2019; Sunny and Shu 2019). The latter are seen as a vital source of green technology and industry development, not least due to their often greater technological variety (Trippl et al. 2020). Suggesting that new companies often emerge in the environment of existing companies or spin-off directly from them (Chapple et al. 2011; Corradini 2019), many studies on the geography of eco-innovations seek to conceptualise change in a logic of path development and regional branching rather than disruptive changes (Cooke 2012; MacKinnon, Dawley, Steen, et al. 2019).

Although research on the geography of transitions agrees on the importance of scientific, political and economic actors in terms of knowledge and skill creation as well as the implementation of financial and regulatory frameworks, it puts much stronger focus on actors from civil society as well as intermediaries (Klitkou and Coenen 2013; Sjøtun and Njøs 2019; Loorbach et al. 2020). This broader actor perspective is also motivated by transition studies' emphasis on the complexity of socio-technical systems as well as the inclusion of the demand side. In particular, civil society actors such as cooperatives, community initiatives or sharing platforms are found to influence transformative change by creating and translating ideas, mobilising broader engagement, raising awareness and providing an environmentally friendly environment (Hawkey 2012; Hansen et al. 2018; Roesler 2019; Fontaine 2020; Loorbach et al. 2020). Beyond knowledge creation, actors from the societal domain take on softer forms of power by producing alternative rationalities necessary for socio-technical change (Fuenfschilling and Binz 2018). Intermediaries, in turn, produce place-based configurations of systemic elements that support sustainability-related change (Hess et al. 2018; Barnes 2019; Sotarauta and Suvinen 2019). Their core function is to span and interconnect subsystems within and beyond territories by creating shared visions, conducting experiments, building trust, spreading legitimacy, providing resources as well as generating and sharing knowledge (Essletzbichler 2012; Blum, Bening, and Schmidt 2015; Lukkarinen et al. 2018).

Besides an overall broader understanding of actors, geographical transition studies differ from those with a pure innovation focus in that they emphasise directionality and hence the inevitability of conflicts and tensions between actor groups. Transition studies emphasise that similar types of actors might take several and varying roles in transition processes (Raven, Schot, and Berkhout 2012), with conflicting interests arise not only from their functional attribution to a specific subgroup like industry or science, but also from their focus on either maintaining or challenging the existing regime (Murphy 2015; Haarstad and Rusten 2016; Strambach 2017). In the perspective of transitions research, powerful regime-level actors, such as incumbent, multi-national firms, operate across spatial level and constrain socio-technical change through unilateral decision-making, power asymmetries and vested interests (Haarstad and Rusten 2016; Fuenfschilling and Binz 2018; Trippl et al. 2020). This perspective is hardly ever explicitly stressed in the parallel, innovation-oriented strand of literature.

Following the geographical transitions literature, the status quo will only be changed by actors who are not closely intertwined with the current system (Veldhuizen 2021). And while small, new firms that emerge from (regional) niches may play a central role in this context, their capacity to effect regime change on their own will often remain limited (Coenen, Hansen, and Rekers 2015). To overcome technological barriers and accelerate transition processes, studies acknowledge the importance of additional competences of new actors as well as state and private financial support (Bento and Fontes 2015; Truffer, Murphy, and Raven 2015; Andersson, Hellsmark, and Sandén 2018), the communication of expectations and counter-narratives on future possibilities through engaged actors (Raman and Mohr 2014; Bauer 2018) and the early involvement of different actors in regional networks, including users and incentivised regime actors (Faller 2016; Vermunt et al. 2020; Rohe and Chlebna 2021). Accordingly, most geographical systems transitions literature takes a much broader and at the same time more differentiating perspective on actors than traditional innovation system studies.

Against this background of debates on stability and change, however, research strands on the geography of transitions and green path development, have more recently converged in developing agency perspectives to explain spatial particularities. In this context, agency stresses the role of (individual) actors and how they affect both industrial paths and trajectories towards sustainability. As such, actors purposefully and deliberately influence innovative and transformative change, which are conditioned by past experiences and geography (Dawley 2014; Steen 2016; Boschma et al. 2017; Sotarauta et al. 2021). Trippl et al. (2020) suggest a distinction between firm-level and system-level agency, both of which are considered necessary. Although firm-level agency in particular includes economic actors' activities that trigger green regional development, the geographical literature on eco-innovation and regional innovation systems has only very sporadically taken up agency perspectives (Dawley 2014; Sotarauta et al. 2021). Research on the geography of transitions, in turn, usually refers more distinctly to the importance of system-level actors and their agency in transforming technological, organisational and institutional configurations (Barnes 2019; Sjøtun 2020). The transition research's interest in these change agents is consistent with its focus on processes that lead to the creation of new assets and the overcoming of path-dependent industrial and institutional regime structures that prevent sustainability transitions from happening (Fuenfschilling and Binz 2018; MacKinnon, Dawley, Pike, et al. 2019; Trippl et al. 2020).

5.4.2 Institutions

The behaviour of actors is inevitably linked to the institutional context. This sets the rules of the game, which can be cognitive, regulative and normative in nature (Coenen, Raven, and Verbong 2010; Davies and Mullin 2011; Binz, Truffer, and Coenen 2016). A general distinction is made between informal institutions such as norms, values or cultures, sometime also designated as conventions, and formal institutions such as rules, laws or regulations. Policies are also often be seen as formal institutions (Capasso et al. 2019). Both types of institutions might impede or enhance eco-innovative and transformative change (Grillitsch and Hansen 2019; Isaksson and Hagbert 2020). From a geographical perspective, institutions have not only a local and regional but also a multi-scalar dimension due to national and supranational technological and industry-wide rules (MacKinnon, Dawley, Steen, et al. 2019).

The diverse geographical literatures on eco-innovations and sustainability transitions agree that informal institutions are central to explaining spatially differentiated development patterns. Where they differ, however, is in their focus on the spatial effectiveness of informal institutions and their manifestation. Research contributions evaluating geographical aspects of eco-innovations usually stress the institutional embeddedness of actors and processes within specific places (e.g., Chapple et al. 2011; DiVito and Ingen-Housz 2019; Grillitsch and Hansen 2019). This builds on the recognition that innovation as a social phenomenon is based on knowledge and interaction, embodied in skills and routines, which in turn are shaped by regional institutional assets (Carvalho, Mingardo, and van Haaren 2012). These have developed over long periods of time in a place-specific manner and influence regional eco-innovative performance (Truffer, Murphy, and Raven 2015), for example in the context of the emergence of green start-ups (Corradini 2019) or the early adoption of environmentally friendly solutions (Losacker and Liefner 2020). Rigid institutional structures, as often found in old industrial regions, pose barriers to green path development and make unrelated diversification more challenging (Boschma et al. 2017; Tödtling, Trippl, and Frangenheim 2020). In essence, studies with a regional science focus engage with regional institutional structures as localised contextual factors to explain spatial variation of eco-innovation activities.

Due to the often global nature of dominant sectors and technologies (socio-technical regimes), transitions research additionally emphasises the role of broader socio-technical contexts independent of space and scale (Coenen and Truffer 2012; Boschma et al. 2017; Grillitsch and Hansen 2019), as these may be just as important for understanding the spatiality of the emergence and stability of industries and technologies as local framework conditions (Truffer and Coenen 2012; Dewald and Fromhold-Eisebith 2015). For example, new and potentially more sustainable products and processes that are not well aligned with the prevailing sector-specific institutions barely diffuse and scale up, irrespective of how conducive the regional context is. This lack of legitimacy is usually accompanied by scepticism and low user acceptance (Späth and Rohracher 2012; Binz, Truffer, and Coenen 2016; Rohe and Chlebna 2021). Just like with a view to actor networks, geographical research on transitions has a more pronounced tendency towards multi-scalar institutional perspectives than established research on eco-innovations (e.g., Strambach 2017).

Just as informal institutions shape places and vice versa, so do formal institutions (Trippl et al. 2020). There is widespread consensus in both the innovation- and transition-oriented geographical literature that policies and environmental regulation are another key driver to achieve green restructuring and systemic changes towards sustainability (De Laurentis 2013; Park and Lee 2017; Hess et al. 2018; Martin 2020). In general, scholarly work finds that policies and priority settings vary substantially across space (Wesseling 2016; Steen, Faller, and Ullern 2019), with regional (innovation) policies able to influence higher level policy frameworks. These regions can well be called transition regions and are characterised by certain governance capabilities that can be inspiring for other territorial units (Cooke 2011). Conversely, (supra-)national policies usually set the conditions and incentives that facilitate or impede implementation at the regional level (Carvalho, Mingardo, and van Haaren 2012; Quitzow 2015; Haarstad and Rusten 2016). However, differences between the research streams exist in the necessity and justification of policies and regulations.

Research on the geography of eco-innovations often sees policies as formal instruments to address problems associated with double externalities of environmentally friendly products and processes. These illustrate that eco-innovations are not only characterised by knowledge spillovers to actors in the innovation phase, but also by bringing about a socially desirable outcome in the diffusion phase, with eco-innovators bearing the total costs (Rennings 2000; Quatraro and Scandura 2019;

Perruchas, Consoli, and Barbieri 2020). As this reduces the incentive to invest in innovation, many studies point to the importance of green technology push policies such as public and private R&D, investment subsidies and venture capital funding (Georgeson, Caprotti, and Bailey 2014; D'Agostino and Moreno 2019; Sunny and Shu 2019). This predominantly supply-side perspective has recently been complemented by work on eco-innovations that also considers market or regulatory pull instruments. In particular, work on (regional) lead markets for eco-innovations emphasises that regulations provide advantages if they addresses place-specific environmental problems. This will both increase demand and diffusion of technologies within and across regions, allowing other territories to follow successful regulatory approaches (Cooke 2011; MacKinnon, Dawley, Steen, et al. 2019; Losacker and Liefner 2020).

Transition studies, on the other hand, point to the importance of policies that are transformational in nature and address various system failures beyond innovation research's focus on market failures (Weber and Rohracher 2012; Magro and Wilson 2019). Transformative policies aim to overcome failures resulting from, among others, insufficient integration of the user/consumer perspective or policy coordination between sectors. Far from being one-dimensional, transformative innovation policies can take various forms and combinations of instruments, i.e. policy mixes (Kern, Rogge, and Howlett 2019), which have to be adapted to regional circumstances in order to ensure their adequate design, implementation and functionality (Magro and Wilson 2019; Tödtling, Trippl, and Frangenheim 2020). Given the complexity of socio-technical systems and the contested ideas of sustainability, geographical transition studies highlight the importance of demand-oriented (innovation) policies that mitigate rigid market and industry barriers. These need to take into account both local endowments and global forces (Coenen, Moodysson, and Martin 2015; Wieczorek 2018; Sjøtun and Njøs 2019; Veldhuizen 2020). In order to increase demand and thus the diffusion of environmentally friendly products and practices, studies suggest fostering networks and learning processes across different spatial and regime scales (Coenen, Hansen, and Rekers 2015; Roesler and Hassler 2019; Martin 2020).

5.4.3 Technological elements

Technological elements as central determinants of systemic change include not only technologies as such (material artefacts) but also the knowledge associated with them (Markard, Raven, and Truffer 2012). On the one hand, there is widespread agreement among the studies of the various literature streams that the emergence and diffusion of technological eco-innovations, such as renewable energy technologies (RETs) or efficiency techniques in buildings, are necessary to cope with environmental challenges. On the other hand, both innovation and transition studies point to the limitations and difficulties of this technological fix and increasingly refer to the dissemination of non-technological solutions and knowledge (Hansen and Coenen 2015; Perruchas, Consoli, and Barbieri 2020).

Geographical research on eco-innovation and green industrial/technological path development usually refers to the context specificity and temporality of (eco-)innovative change (Gibbs and O'Neill 2017; Kemp et al. 2019). At the same time, eco-innovations are more complex and rely on diverse knowledge inputs from various actors in the innovation system (Barbieri et al., 2020; De Marchi, 2012). This results in a place and path dependencies of sustainability processes, with technological relatedness having a significant influence on the green diversification of regions (Colombelli and Quatraro 2019; Santoalha and Boschma 2021). Against this background, the availability of related skills and capabilities facilitate regional knowledge spillovers within and across sectors and industries (Antonioli, Borghesi, and Mazzanti 2016; Losacker 2020).

Contrary to what is often assumed in the transitions literature, data of Santoalha and Boschma (2021) and van den Berge, Weterings, and Alkemade (2019) suggest that a specialisation in unsustainable technologies does not necessarily hamper the green development of regions and may even provide necessary capabilities for it. In essence, geographical research on eco-innovations focuses predominantly on interdependencies at the same spatial level (Rohe 2020), with a view e.g., to the question of whether the environmental performance and innovation activities in a given region are influenced by those of adjacent ones (Costantini, Mazzanti, and Montini 2013; Quatraro and Scandura 2019; Benedetti, Palma, and Postiglione 2020).

Although transition studies do not negate the importance of horizontal interdependencies, the emergence of sustainable solutions is attributed to niches that are not necessarily confined to a specific spatial level (Sjøtun 2020). In line with the multi-level perspective, they form protected spaces that allow the development and experimentation of technologies detached from institutionalised regime structures (Binz, Truffer, and Coenen 2016; Lukkarinen et al. 2018; de Haan et al. 2021; Fusillo, Quatraro, and Usai 2022). While, by definition, these do not need to be local, geographical transitions research emphasises that geographical and social proximity tend to facilitate the building of trust and exchange of ideas. Unlike established innovation studies which primarily emphasise the localisation of research-intensive technology creation and knowledge transfer, much research on the geography of transitions focuses on the localisation of new ideas, imaginaries and alternative practices in localised, socio-cognitive spaces (Longhurst 2015; Sengers and Raven 2015; Meelen, Frenken, and Hobrink 2019).

Transformative change is thus initiated and scaled up, with both bottom-up and top-down activities between spatial levels resulting from a dynamic process of interdependencies (Dewald and Fromhold-Eisebith 2015; Sengers and Raven 2015; Radinger-Peer and Pflitsch 2017). As such, vertical linkages across scales, i.e. multi-scalar interdependencies have a decisive influence on the transformation of sectoral structures. The upscaling and downscaling of transformative practices, both between niches and regimes and between spatial levels, have been widely confirmed in transition studies (e.g., Cooke 2010; Späth and Rohracher 2012; Gibbs and O'Neill 2014). Similar to these ideas, Losacker and Liefner (2020) developed the regional lead market framework and empirically demonstrate that regions can drive national and international diffusion of transformative innovations when a competitive advantage is achieved through an early market formation and technological capabilities. In this case, regions "act as (…) lighthouses for eco-innovation to other regions and countries" (Cooke 2011, 106).

Conversely, the national and international level influence regions, e.g., through policy and agenda setting (Lovio and Kivimaa 2012; Mazzanti 2018; Njøs et al. 2020), dominant rationalities (Fuenfschilling and Binz 2018) and flows of knowledge (Chiarvesio, De Marchi, and Maria 2015; Rohe 2020). Whether and to what extent change towards sustainability is fostered also depends on the regional absorptive capacity, which is seen as crucial for the identification, assimilation and exploitation of external information and technological developments (Bento and Fontes 2015; Blum, Bening, and Schmidt 2015).

Table 3: Main findings on actors, institutions and technological elements by broader direction of research

Geographical research oriented towards…	Actors	Institutions	Technological elements
…eco-innovations	• Role of actors from academia, politics and business (triple helix) typically assessed within specific territories • Predominant focus on established companies and start-ups • Logic of path development is emphasised, as newcomers often emerge in the environment of existing actors • Actors are seen as drivers and facilitators of change	• Both formal and informal institutional structures seen as localised contextual factors that explain spatial variation of eco-innovation activities • Institutions develop in a place-specific manner over long time periods • Policy instruments important to overcome market failures associated with double externalities of eco-innovations • Dominance of supply-push policies to enhance green technology development	• Complex eco-innovations rely on context-specific and temporal conditions that result in path and place dependencies • Regional technological relatedness influences green diversification processes • Spillover and transfer of research-intensive knowledge and technologies within and between regions • Focus on technology development
…sustainability transitions	• Potential relevance of a multitude of actors from all domains • Strong focus on civil society and intermediary actors • Actor networks transcend spatial scales • Similar actors can take on different roles that vary over time and space • Conflicts and tensions between actor groups • Incumbent actors constrain socio-technical change, while niches actors are crucial for changing the status quo	• Institutional embeddedness of technologies and sectors beyond specific territories • Multi-scalar institutional perspectives • Legitimacy of environmentally friendly products and processes is crucial to change sector-specific institutions • Policy interventions –policy mixes– oriented towards transformational failures • Importance of demand-side policies that focus on consumers' perspectives and mitigate industrial barriers	• Multi-scalar perspective on technology emergence and diffusion • Importance of niches (protected spaces) and local experimentation to exchange ideas, imaginaries and practices • Bottom-up and top-down activities between spatial levels to scale transformative practices and technologies
Similarities	• Actors generate knowledge and influence power within networks • Since geographical proximity facilitates diffusion and exchange processes, actor networks are often locally or regionally constituted • Agency affects industrial paths and transformative trajectories towards sustainability	• Formal and informal institutions impede or enhance eco-innovative and transformative change • Policies and regulation vary across space, with (supra)-national priority settings potentially influencing sub-national territories and vice versa	• Both technological and non-technological solutions (including knowledge) influence systemic change • Technological interdependencies beyond the region level

5.5 Discussion

Covering more than a decade of numerous conceptual and empirical contributions, this systematic review of the literature synthesised findings from related but so far mostly co-evolving research streams on sustainability oriented innovation and transitions. From a comparative perspective, this allows us not only to identify distinctive characteristics of either stream but also complementarities that harbour numerous, in part obvious potentials for conceptual cross-fertilisation (see also Binz et al. 2020; Hansmeier, Schiller, and Rogge 2021). We discuss these along the three previously mentioned categories of analysis of actors, institutions and technologies. A first aspect concerns the question by which actors innovative and transformative processes can - and should primarily - be driven. Here, the two broader literature directions put different emphases on the role of specific actors. Established eco-innovation research tends to at least equally consider opportunities for change within existing path dependencies and actor coalitions (e.g., “path renewal”) (Cooke 2012; MacKinnon, Dawley, Steen, et al. 2019), whereas transition research tends to regard the overt majority of incumbents as obstructive (“regime”) and hence to suggest that radical change driven by actors outside established regime structures will be required (Späth and Rohracher 2012; Fuenfschilling and Binz 2018). Although established research does include inquiry into the conditions under which new paths emerge (e.g., Strambach and Pflitsch 2020; Trippl et al. 2020), there is still a lack of differentiated empirical findings, particularly on the role and relationship of new and established actors.

More recently, the emergence of research on (change) agency may provide a possible field of convergence as it contributes to the explanation of spatial differences beyond specific contextual factors (e.g., Sjøtun 2020; Sotarauta et al. 2021). At the same time, recent findings suggest that roles in the development and use of environmentally friendly solutions are less clear-cut than assumed in transition studies (e.g., van den Berge, Weterings, and Alkemade 2019; Santoalha and Boschma 2021) and that the assumption that change is driven, even initiated, by regime outsiders alone may in itself also be lacking. Accordingly, we believe that an integration of insights from both research directions and an inclusive perspective on the diverse conditions for change agency would provide more clarity about the influence and scope of the diverse driving forces observable in empirical reality.

A second dimension of inquiry for which such an integration could be beneficial concerns the question which role future conceptual frameworks should attribute to institutional barriers of eco-innovation and transitions. In the geographical literature on eco-innovations, optimistic assumptions prevail concerning the potential enabling impact that supportive framework conditions and institutional setting can have on actor behaviour. As common within economics and business administration, eco-innovation tends to be framed as the outcome of (more or less) rational, entrepreneurial choices contingent on regulation, policies, markets and institutions (e.g., Antonioli, Borghesi, and Mazzanti 2016; Horbach and Rammer 2018). Future research in that area will therefore have to better consider the effects of sector or technology-specific institutions –both on the development and diffusion of (non-technological) eco-innovations. In this endeavour, it could benefit from relevant insights that transition studies already gained concerning institutional arrangements that drive or prevent sustainable change, not least with a view to the role of the demand side. However, this would also require a shift in analytical perspective as institutions cannot simply be understood as pure spatially-bound contextual factor but require a multi-level, relational perspective on geography.

Studies within sustainability transitions, to the contrary, tend to emphasise dimensions of obstructive regimes, coalition building, power relations, agency and conflict. Consequently, their analytical- and policy-related conclusions tend to suggest that changes in regulation can only effect transitions when combined with targeted activities of actor coalitions at the niche level - including policy making not only as a framework, but instead as a directly involved, constitutive part of a dynamically evolving system (e.g., Meelen, Frenken, and Hobrink 2019; Roesler and Hassler 2019). That said, more established findings that the geographical eco-innovation literature could provide on the relevance of institutions, path dependencies and other, more localised framework conditions remain relevant. To uphold this perspective could indeed remain valuable for future inquiry beyond the core literature of sustainability transitions.

A third dimension of inquiry concerns the role of regions' structural characteristics with regard to technologies and knowledge. So far, the sustainability transitions literature focuses quite prevalently on the role of specific niches and experimentation. While these insights are valuable, this review suggests that the existing literature within sustainability transitions might well profit from insights on the territorial relationship between regional technological capabilities and socio-technical change which has so far not been sufficiently explored. Although, for example, Grillitsch and Hansen (2019) have looked at different types of regions, the question which particular opportunities or challenges, for example, regions with an mature technological and industrial base face during transitions remains open.

Arguably the existing literature on the geography of eco-innovation provide many relevant insights into such relations already or - even if one chooses not to share their epistemological premises - at least relevant points of departure for future inquiry. Thus, our analysis suggests that the sustainability transitions literature could profit from the established eco-innovation discourse as much as the other way round. Yet, some of the few existing cross-over studies on regions' role of driving green innovation and restructuring have begun to pursue the avenue of inquiry, even if further ground remains to be covered (e.g., Calignano, Fitjar, and Hjertvikrem 2019; Losacker and Liefner 2020).

5.6 Conclusion

As complex and multi-scalar processes, eco-innovative and transformational change require additional and multidisciplinary research efforts to develop a better understanding of and more precise insights into territorial and sectoral interdependencies. Against this background, this systematic review of the diverse geographical literature on eco-innovations and sustainability transitions has demonstrated how future efforts to that end could profit from a better integration of insights from the diverse strands of literature with a view to three central aspects of inquiry. While acknowledging and outlining substantive differences, we maintain that both broader lines of research that we have identified are neither conceptually nor epistemologically irreconcilable at a fundamental level.

Despite the diverse and increasingly converging work, further research is needed to promote the integration of an in part still rather fragmented discourse. On a more general level, a central task of (economic) geography remains to explore whether the green transition exacerbates or mitigates spatial inequalities. In other words, whether lagging or peripheral regions can catch up or whether innovation hotspots continue to gain importance. This has also key implications for recent work on "just transitions" (e.g., Jenkins, Sovacool, and McCauley 2018).

While the benefit of integration is already obvious for the existing discourses around agency, institutions and technologies, we expect that it will gain additional relevance in those on individual and psychological characteristics that are only just emerging (e.g., Huggins and Thompson 2021). Against the background of the importance of converging interests and values, newer methodological approaches such as the socio-technical configuration analysis seem helpful (Heiberg, Truffer, and Binz 2022), which go beyond idiosyncratic case studies and static spatial concepts and make complex spatial dynamics on social and technological elements tangible.

Beyond arriving at a more concise conceptual understanding of ongoing spatial transition processes, our findings also suggest that a denser mutual recognition of both discourses could enable better and more robust policy advice, e.g., with a view to how regions can steer and enable change towards sustainability (see also Tödtling, Trippl, and Frangenheim 2020; Bugge, Andersen, and Steen 2021). Given the complexity of systemic change, research is also needed on how the multi-scalarity of transitions goes hand in hand with political realities, according to which regional decision-making processes are, if at all, confined to one's own territory. Moreover, insights on the practicability and suitability of policies aiming at environmentally friendly products and practices at the regional level are still limited. Therefore, it might also help contextualise the spatial implications of various increasingly transformative (innovation) policies that seek - in a pragmatic, sometimes a-theoretical manner - to trigger change in a variety of ways.

6 Incumbents and Start-ups as Eco-Innovators in Different Types of Regions: Insights from the Transport Sector in Germany

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Abstract

The regional variety of actors is considered a key determinant in the last decade's rich literature on the geography of eco-innovation and sustainability transitions. However, little is known about the extent to which regions differ in their specialisation of new and established eco-innovation actors. In this article, we propose a regional typology based on specialisations in green incumbents and start-ups in the German transport sector. We find that while many regions display either specialisations in start-ups or incumbents some regions manage to specialise in both actor types. The revealed regional heterogeneity in actor specialisations has important implications for regional policy.

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6.1 Introduction

The greening of the economy is decisive to achieve wider socio-technical transitions towards sustainability. The transport sector is under particular pressure to transform; it is largely based on fossil fuels and accounts for approximately one quarter of energy-related and 15 percent of global greenhouse gas (GHG) emissions (IPCC 2022). As more goods and passengers are transported by road, rail, air and water, sector emissions in countries of the Global North are even significantly higher (20 – 30 percent), with no decline observed over the years (Fransen et al. 2019; ClimateWatch 2022). Other negative environmental impacts result from land sealing, local pollution as well as noise emissions and microplastic waste (Demirel et al. 2008; Baensch-Baltruschat et al. 2020).

Countries and regions differ not only in terms of causing global environmental challenges, but also in addressing and solving them. The latter is the focus of research on the geography of eco-innovation and sustainability transitions that has emerged in the past decade (Hansen and Coenen 2015; Binz et al. 2020; Hansmeier 2021; Losacker et al. 2021), pointing to the importance of place-specific and regional factors for eco-innovation processes. Geographical and related forms of proximity facilitate the emergence, diffusion and application of knowledge and innovation through access to networks and resources. As analysed by previous work, the place-specific nature of green technology, industry and regional development as well as sustainability transitions is mainly due to (in-) formal institutions including policies (e.g., Bugge, Andersen, and Steen 2021; Gibbs and Jensen 2022), technological capabilities (e.g., Corradini 2019; Santoalha and Boschma 2021) as well as local actors (e.g., Binz, Truffer, and Coenen 2016; MacKinnon, Dawley, Steen, et al. 2019).

As regional conditions of eco-innovation development are of core interest in the pertinent literature, numerous studies focus on the roles and multitude of regional eco-innovators. These include primarily actors from industry, politics and academia, but also intermediaries and societal actors (e.g., Gustafsson and Mignon 2020; Trippl et al. 2020; Gibbs and Jensen 2022). However, the relationship between established and new actors is also crucial to increase our understanding of regional sources of sustainability transitions (van den Berge, Weterings, and Alkemade 2019). Although innovation studies have analysed the influence of regional contexts on the emergence of eco-innovations in incumbent firms (e.g., Klitkou and Coenen 2013; Horbach and

Rammer 2018) as well as in green start-ups (e.g., Colombelli and Quatraro 2019; Corradini 2019), both aspects have hardly been considered together in order to better grasp the regionally prevalent balance of eco-innovation actors. On the other hand, transition studies' interest in stability and change is reflected both in the focus on the forces of inertia and radical novelty depending on experimental alignment (Boschma et al. 2017; Gibbs and Jensen 2022). While overarching studies on different combinations of regional actors are missing, recent studies argue, however, that incumbents operate quite heterogeneously and do not only preserve the status quo, as often assumed. Accordingly, change can emerge from both incumbents and new entrants (Steen and Weaver 2017; Turnheim and Sovacool 2019; Strambach and Pflitsch 2020).

The aim of this paper is to gain a better understanding of regions' specialisation - i.e. the relative importance - with respect to eco-innovation activities of incumbents and start-ups in the transport sector. Following Hockerts and Wüstenhagen (2010), we conceive green incumbents as organisations, usually firms, that are well established and engage in eco-innovation activities, while start-ups are recently founded companies with an innovative and environmentally friendly business model or product. By focusing on specialisations, we intentionally focus less on how the joint existence of established and newly founded companies develops (which would be a biased comparison), but rather on the extent to which the two types of actors in a region have already progressed in the process of greening. In addition to the general question of how regions differ in terms of relative actor specialisations, we are particularly seeking to analyse the joint regional specialisation of green transport incumbents and start-ups. Finally, we test which regional conditions explain the observed spatial patterns.

Empirically, we estimate the greening of incumbents based on patents, which are filed almost exclusively by large companies in the transport sector (Eurostat 2014) and green start-ups via data from the Mannheim Enterprise Panel (MUP) for the period 2009-2018 in the 96 functional spatial planning regions in Germany. As we analyse not only technological change via patents but also business model or service innovations, the combined analysis allows us to examine the broader eco-innovative change necessary for sustainability transitions in the transport sector (Tödtling, Trippl, and Desch 2022).

The outline of this paper is as follows. The next section presents the theoretical and empirical status-quo of geographical research on eco-innovators. Based on this, hypotheses are derived. Subsequent sections describe the data and methods of this study before we present key findings. This is followed by a discussion of the results and a conclusion, pointing to further research possibilities and policy implications.

6.2 Regional perspectives on eco-innovation incumbents and start-ups

Innovations are the result of new combinations of goods, skills, knowledge, techniques and resources. This implies the need for collaborating and interactive relations, which led to the systemic understanding, i.e. sectoral, technological, regional/national, of innovation emergence and application (Edquist 1997; Moulaert and Sekia 2003). From the perspective of geographical research on eco-innovations and sustainability transitions, questions arise not only about spatial differences in technology and industrial development (Capasso et al. 2019; Tödtling, Trippl, and Frangenheim 2020), but also about the relevant actors. More precisely, whether, according to the Schumpeterian dichotomy, the necessary change is primarily carried out by established actors or whether new entrants are required and how regions differ in this respect (Turnheim and Geels 2019; Trippl et al. 2020).

6.2.1 The role of incumbents in eco-innovation activities

Given the heterogeneity of actors that constitute complex innovation and socio-technical systems, a multiplicity of incumbents can be identified. Hence, incumbents exist and act to varying degrees at different (spatial) levels and social spheres, with incumbent behaviour particularly visible among powerful firms and government actors (Ansari and Krop 2012; Turnheim and Geels 2019). Incumbent actors are closely linked to the regime concept of transitions research, according to which institutionalised (in-)formal rules stabilise socio-technical systems that lead to path dependencies and incremental changes (Miörner and Binz 2021). These path-dependent developments are the result, for example, of incumbent firms predominantly adhering to existing and potentially successful business logics, which slows down or prevents transitions towards sustainability (Bohnsack, Pinkse, and Kolk 2014; Steen and Weaver 2017).

With regard to the transport sector, these patterns are particularly evident for the globally dominant automotive regime that has evolved for more than a century, leading to stable production and consumption practices (Sengers and Raven 2015). This regime has been manifested through technical, institutional and social adaptations with little system-changing innovation activities over the last decades (Sovacool, Noel, and Orsato 2017). Although established firms are active in regional and national research efforts and production, they are also strongly integrated into international markets and collaborations, promoting similar transport modes around the world (Nilsson, Hillman, and Magnusson 2012).

Despite these characteristics, however, innovation and transition studies point to a more diverse picture of incumbents (e.g., Ansari and Krop 2012; Steen and Weaver 2017) and pluralising perspectives on incumbencies across regions and sectors (Turnheim and Sovacool 2019). These views are based on the findings that established firms and other incumbents may pursue eco-innovation development. Although incumbent firms seem less likely to be initial leaders of environmentally oriented innovation (Geels 2011), differences emerge depending on the industry environment and firm properties, as well as challenges from new entrants (Ansari and Krop 2012; Turnheim and Sovacool 2019). In addition, there are varying institutional field logics, such as differences in standardisation (Dewald and Achternbosch 2016), which are likely to translate into spatial differences (Miörner and Binz 2021). For the transport sector, incumbents are significantly involved in the development of environmentally friendly transport technologies and business models in regions, e.g., shared or autonomous mobility (Bohnsack, Pinkse, and Kolk 2014; Nilsson and Nykvist 2016; Meelen, Frenken, and Hobrink 2019). At the same time, it was found that incumbents can also influence the institutional framework in a way that promotes transforming the transport sector at the regional level (Miörner and Trippl 2019; Bugge, Andersen, and Steen 2021).

While transformative and eco-innovation activities were initially hardly analysed from a geographical perspective, their spatial manifestation has received increasing scientific attention over the past decade (Hansen and Coenen 2015; Hansmeier 2021). Numerous geographical studies point to the importance of diversified capabilities and knowledge bases at the regional level, which go beyond internal innovation capacities. In this context, the relatedness to pre-existing capabilities is of particular relevance for green regional diversification (Montresor and Quatraro 2020; Santoalha and Boschma

2021). As such, a narrow regional specialisation seems insufficient (Coenen 2015) and agglomeration effects, clustering, co-location and linkages of various actors are found to positively impact eco-innovations (Del Río, Peñasco, and Romero-Jordán 2016; Sunny and Shu 2019; Horbach 2020). This is in line with the frequently confirmed finding that innovation activity in general and complex economic activities in particular are concentrated in more densely populated regions (e.g., Balland et al. 2020; Mewes and Broekel 2022). With green and non-green innovative developments predominantly observable in urban or metropolitan regions (see also Grillitsch and Hansen 2019), we propose the first hypothesis:

Hypothesis 1: *The specialisation of eco-innovation transport incumbents is more likely in regions with a higher population density.*

6.2.2 The role of start-ups in eco-innovation activities

Eco-innovative start-ups are crucial in transforming production and consumption patterns, both within and beyond the region. They introduce environmentally friendly product innovations and green technologies, but also new business models and services (Colombelli and Quatraro 2019; Bioret, Dechezleprêtre, and Fadic 2021). New entrants seem to be particularly influential in the early stages of an industry transformation (Hockerts and Wüstenhagen 2010), as they bundle new products and services in a unique way or generate new knowledge and capabilities that notably deviate from previous knowledge bases. Start-ups can therefore boost eco-innovation activities and influence established players (Bohnsack, Pinkse, and Kolk 2014; Dewald and Achternbosch 2016; Nilsson and Nykvist 2016). This is also true for the transport sector, in which start-ups play a leading role in the development of eco-innovation despite the above-mentioned strong regime structures. In the case of electric mobility, for example, start-ups seem to have developed new products and business models around the same time as incumbents (Bohnsack, Pinkse, and Kolk 2014; Sovacool, Noel, and Orsato 2017; Tödtling, Trippl, and Desch 2022).

Against this background, conceptual and empirical research on knowledge spillovers shows that start-ups benefit greatly from unused and non-commercialised ideas and knowledge of established actors (e.g., Klitkou and Coenen 2013; Colombelli and Quatraro 2019; Cojoianu et al. 2020). Although the importance of existing structures varies greatly between sectors (Dewald and Achternbosch 2016), geographers in the field of regional studies and transitions research argue that entrepreneurial activities of start-ups and spin-offs are an essential mechanism of regional branching into related and new industries (Boschma et al. 2017; MacKinnon, Dawley, Steen, et al. 2019). Green industrial development in particular benefits from new innovation actors, as they are especially capable of developing skills and knowledge combinations beyond region-internal path dependencies. The process of green path creation is therefore more likely to occur in regions where the support structures and the existing skill base are well-developed (Tödtling, Trippl, and Frangenheim 2020; Trippl et al. 2020; Gibbs and Jensen 2022). Given the aforementioned findings, we derive the second hypothesis as follows:

Hypothesis 2*: Green transport start-ups are more likely to emerge in those regions that are also specialised in eco-innovation transport incumbents.*

Start-ups are particularly dependent on the external availability of knowledge and networks, not only due to the greater complexity of environmental innovations but also because of limited internal resources (Horbach 2020). Against this background, a large number of recent studies have examined regional determinants of green start-up emergence. First, it has been shown that the knowledge accumulated in a region is positively associated with the emergence of green start-ups (e.g., Colombelli and Quatraro 2019; Horbach 2020; Coll-Martínez, Malia, and Renou-Maissant 2022). As new actors extensively build on pre-existing structures, a differentiated but complementary knowledge pool is particularly crucial (Giudici, Guerini, and Rossi-Lamastra 2019; Vedula, York, and Corbett 2019). Likewise, Cojoianu et al. (2020) and Coll-Martínez et al. (2022) report a positive correlation between regional human capital endowment as well as the presence of research institutions and the emergence of new eco-innovation entrants. Looking at the technological dimension, it is interesting to note that spillovers from both green and non-green knowledge creation seem to influence green regional start-up activities (Colombelli and Quatraro 2019; Cojoianu et al. 2020). Thus, we derive the following hypothesis:

Hypothesis 3*: The higher the share of highly qualified people in a region, the higher the likelihood that this region is specialised in green transport start-ups.*

In addition to skills and technological capabilities, regulation and (regional) policies influence green start-up activities. For example, by directly promoting eco-innovative and environmentally friendly start-ups, negatively impacting non-green start-ups or creating demand incentives, thereby strengthening market certainty for green start-ups (Giudici, Guerini, and Rossi-Lamastra 2019; Hoogendoorn, van der Zwan, and Thurik 2020; Horbach 2020). Moreover, numerous studies show that regions' informal institutional framework conditions are crucial. As such, social norms, shared meanings, behavioural patterns and environmental awareness influence firm formations and green entrepreneurship at the regional level. On the one hand, these can lend additional legitimacy to environmentally friendly technologies and practices, and on the other hand, they can simplify opportunity recognition. Both factors increase regional eco-innovative firm entry (e.g., Vedula, York, and Corbett 2019; Cojoianu et al. 2020; Tödtling, Trippl, and Frangenheim 2020).

6.3 Case and data description

To identify and explain activities of eco-innovation incumbents and newcomers at the regional level, we use two different data sources. As incumbent actors usually only publish aggregate data, we rely on patent data to proxy their eco-innovation activities. Of the company-related patents filed at the European Patent Office (EPO), the majority are held by large corporate entities; in the field of transport even more than 95 percent (Eurostat 2014). Accordingly, we can use patent applications as a very direct proxy of inventive activities driven by incumbents. In contrast, activities of new entrepreneurial market entrants can be measured directly by the number of start-ups. Given the novelty of activities in the domain of green transport, a large share of new firms' activities can thus be considered innovative (e.g., Vedula, York, and Corbett 2019; Cojoianu et al. 2020). Before describing the data, we first characterise the transport sector in Germany.

6.3.1 The German transport sector

Eco-innovative activities in the German transport sector are of crucial importance, both from an economic and environmental perspective. With respect to the former, firm and employment data for the German manufacturing sector suggest large differences by mode of transportation. In 2021, more than 220 companies with about 130,000 employees were involved in the production of ships and boats, rail vehicles, air- and spacecraft, as well as motorcycles and bicycles. In contrast, the automotive industry alone comprised around 1,000 companies (manufacturers and suppliers) with approximately 830,000 employees, with medium to large companies dominating (Destatis 2023).

This economic importance of the automotive industry in Germany has evolved over many decades. With a share of around 4 to 5 percent of gross value added, it is one of the key industries in Germany. In terms of the volume of cars and commercial vehicles produced, Germany ranks fourth behind China, the US and Japan. In the years before the coronavirus pandemic, annual production amounted to around 5 million vehicles, of which an average of three quarters were exported. The international orientation of the automotive industry is reflected not only in the sales markets, but also in global (pre-)production networks. At the same time, automotive manufacturers (OEMs) and suppliers often locate in close proximity to each other, forming industrial clusters within Germany. Although many of the OEMs headquarters are located in the south of Germany, for example in the regions of Stuttgart and Munich, the production facilities and plants are spread across all parts of the country (Viñallonga et al. 2022).

In addition to economic aspects, the transformation of the transport sector is critical to mitigating climate change. In Germany, 90 percent of negative climate effects in the transport sector are attributable to motorised passenger and freight transport by road and air. Increased sustainability therefore requires a mobility transition based on various elements. Besides the avoidance of traffic through, for example, shorter distances and adapted logistics processes, it is primarily a matter of shifting traffic to other means of transport (Allekotte et al. 2021). More recently, the focus has also increasingly been on (digital) mobility services (carsharing, on-demand services, etc.), which are becoming more important in German cities and represent more climate-friendly transportation alternatives (Krauss, Krail, and Axhausen 2022). Third, it is essential to improve existing modes of transport, mainly by changing drive systems (e.g., electrification, hydrogen, etc.) (Allekotte et al. 2021). Accordingly, it is not only the greening of incumbents that is important, but also the innovative activities of new entrants that open up alternative transport options.

6.3.2 Patent data

Patents are a key measure in innovation research and related fields to study the emergence and diffusion of knowledge and technological inventions. The use of patent data is accompanied by limitations, such as the prevailing focus on technologies, the low informative value with regard to the quality and impact of inventions and the possible non-patentability thereof. However, patents are particularly valuable for geographical analyses because they allow to trace the production of (technological) knowledge in a comprehensive and spatially nuanced way (Griliches 1990; van den Berge, Weterings, and Alkemade 2019).

In this study, the PATSTAT database of the European Patent Office (EPO) is used. In a first step, we collect all patent applications with priority dates from 2009 to 2018 and assign them regionally using the inventors' addresses. Like van den Berge et al. (2019), we use whole counts in the case of multiple inventors, hence we consider knowledge to be a non-divisible good. Since an overly small-scale approach would risk that many regions have no or only a small volume of patents, we resort to the 96 German planning regions. These represent, similar to U.S. labour market areas, functional territorial units[5] and are generally composed of several districts ("*Kreise*" / NUTS3 regions). At the same time, this regional setting allows annual socioeconomic data to be aggregated from the municipal or district level. In a second step, we aim to identify all patents from the transport sector as well as those classified as green transport technologies. For the former, we draw on the WIPO technology concordance, which links codes of the International Patent Classification (IPC) to technology fields (Schmoch 2008). To identify green transport technologies, we rely on the Y02 class of the Cooperative Patent Classification (CPC), an extension of the IPC (see Table A 3 in Appendix B for a detailed overview of data sources and search strategies). The subgroup Y02T contains patents related to climate change mitigation technologies in the transport sector, covering road, rail, air and maritime / waterways transport technologies as well as enabling technologies such as charging of electric vehicles and fuel cells (OECD 2016; van den Berge, Weterings, and Alkemade 2019; Coll-Martínez, Malia, and Renou-Maissant 2022). Thus, for the ten-year observation period, we identified 46,228 patents in the technology field of transport and around 15,000 patents are classified as green transport technologies.

[5] Empirical analyses of regional innovation activities often use administrative territories, such as the NUTS regions in European countries (e.g., Corradini 2019; Montresor and Quatraro 2020; Santoalha and Boschma 2021). Functionally delineated regions, however, have the advantage of reflecting economic linkages (e.g., via commuter linkages) and, hence, minimising distortions due to possible differences of the inventor and applicant location in patent documents.

6.3.3 Start-up data

The data used for (green) start-up analyses are taken from the Mannheim Enterprise Panel (MUP) which is generated by the ZEW – Centre for European Economic Research since 1992. By cooperating with the largest German credit rating agency "Creditreform e.V.", which contributes data twice a year on the total German corporate landscape, the MUP provides a comprehensive micro database on legally independent companies. As a result, parent companies and subsidiaries are reported separately. In total, it contains detailed information on around 9 million economically active and closed companies (Bersch et al. 2014; Krieger et al. 2021).

Unlike research that identifies and examines green start-up activities via survey data (e.g., Hoogendoorn, van der Zwan, and Thurik 2020; Horbach 2020), the MUP, with a coverage of about 90 percent of the full stock of firms[6], allows for more representative studies of business dynamics over longer observation periods and small-scale disaggregation (Bersch et al. 2014). Although the mere number of start-ups does not necessarily reflect their quality or impact (Cojoianu et al. 2020), the measure in fact offers a suitable way of covering entrepreneurship activities of a wide range of economic actors at the regional level.

Of particular importance for the analyses in this paper is the information on the company address for the spatial allocation, the date of the foundation for the temporal limitation and the classification of economic activities (NACE Rev. 2). The latter is used to exclude service-oriented and predominantly non-innovative sectors such as wholesale, the hospitality industry and public administration, and to delineate the transport sector (see Table A 3 in Appendix B). Again, we use the years 2009 - 2018 as the observation period and the 96 German planning regions as the units of analysis.

Green start-ups in the transport sector cannot be identified in the MUP by sector assignments. Instead, we follow previous studies and use a keyword-based search strategy (e.g., Shapira et al. 2014; Rogge and Schleich 2018). We derive the technology and sector-specific search terms for green transport start-ups from various databases and sources: the Y02T patent class, transport start-ups listed in the "StartGreen"

[6] Very small firms, such as freelancers, which do not always appear in commercial registers, are missing from the dataset (Bersch et al. 2014). However, it can be assumed that their absence does not bias the present analyses.

network[7] and the work by Cojoianu et al. (2020) (Table A 3 in Appendix B). To check the validity of the identified companies, we screened their brief description and conducted internet searches where necessary. This step eliminated those that are not applicable (e.g., companies primarily active in the energy sector). On the other hand, we add those green transport related start-ups that were not initially found, but appear in the "StartGreen" network or received funding by the German Federal Environmental Foundation (DBU).[8] Overall, of the 42,000 start-ups related to the transport sector, about 900 can be classified as eco-innovative.

6.4 Regional specialisations in eco-innovation actor activities

Against the background of this paper's core empirical project, the subsequent methodological section develops approaches to analyse the regional prevalence of green incumbents and green start-ups. As we are interested in identifying the relative importance of specific actor types in regions, this analysis focuses on eco-innovation actor specialisations. Irrespective of the absolute innovation capacity, it seeks to determine whether the current share of green actor activity in a region's transport sector is above or below national average. By analysing this situation separately for both incumbents and start-ups, it is possible to distinguish between different types of regional eco-innovation actor specialisations.

6.4.1 Measuring a region's actor specialisation

An established and common practice in (economic) geography research is to measure specialisation based on the location quotient (LQ). The LQ allows to determine whether a region is technologically or economically specialised compared to all other regions over a given period of time. Usually, LQ > 1 indicates above-average specialisation, LQ = 1 average specialisation and LQ < 1 below average specialisation. Similar to (Losacker and Liefner 2020) and Horbach et al. (2014), we normalise the specialisation indicators between +100 and -100, with positive values indicating

[7] "StartGreen" is a digital information and networking portal for sustainability oriented start-ups in Germany and is operated by the Borderstep Institute for Innovation and Sustainability (https://start-green.net/netzwerk/)

[8] As a foundation of the Federal Republic of Germany, the DBU supports projects which protect the environment, particularly focusing on small and medium-sized enterprises (https://www.dbu.de/2548.html).

above-average regional specialisations. In the following, we will refer to the normalised LQs as the relative patent advantage (RPA) and relative start-up advantage (RSA). For each region r in the green transport domain g the indicators are given by:

$$RPA_{rg} = 100 \times \tanh \ln \left[\frac{p_{rg}/\sum_r p_g}{p_{rt}/\sum_r p_t}\right] \tag{1a}$$

$$RSA_{rg} = 100 \times \tanh \ln \left[\frac{s_{rg}/\sum_r s_g}{s_{rt}/\sum_r s_t}\right] \tag{1b}$$

Both specialisation measures are calculated as the relation of green transport activities to patent p or start-up activities s in the transport sector t. This allows to control for appropriate baselines, as regional specialisations in environmentally friendly innovation activities might depend on strong activities in the overarching transport sector.

6.4.2 Regional typology of eco-innovation actor specialisations

The comparison of the relative patent and start-up advantage enables us to create a typology of the 96 German spatial planning regions. The RPA and RSA are determined for each region for the entire period from 2009-2018, allowing to depict four different types of regional eco-innovation actor specialisation in the transport sector (Figure 3):

1. Hotspot: Region with both above-average green start-up and incumbent specialisation.
2. Start-up-driven: Region with above-average green start-up specialisation but below-average green incumbent specialisation.
3. Incumbent-driven: Region with above-average green incumbent specialisation but below-average green start-up specialisation.
4. Laggard: Region with both below-average green start-up and incumbent specialisation.

When looking at the distribution of regions by type, it is noticeable that 35 of the 96 regions have neither a start-up nor an incumbent specialisation. These so-called laggard regions represent the largest share (approximately 37 percent), followed by 29 regions in which the greening in the transport sector is driven to an above-average extent by start-ups but less by established actors. Conversely, 18 regions are incumbent-driven and at the same time have a below-average green start-up specialisation. Only 14 regions, i.e. a minority of roughly 15 percent, can be categorised as green transport hotspots, featuring specialisation in both green start-ups and green incumbents.

Overall, this typology reveals a relatively heterogeneous and ambiguous picture of regional eco-innovation actor specialisations in the transport sector in Germany. This initial finding is remarkable in that it neither suggests that start-ups and incumbents mainly emerge in spatial proximity due to the importance of knowledge spillovers and technological specialisation, nor does it seem to support that eco-innovations primarily emerge outside established structures, as conceptualised in transition studies. In the latter case, we would expect a more negative correlation between incumbent and start-up specialisation, while a co-occurrence of start-ups and incumbents would show a positive correlation between RPA and RSA, i.e. that regions fall primarily into either the laggard or the hotspot category. Rather, our descriptive results corroborate the findings of recent work. Not only does the importance of specific eco-innovators vary between regions (e.g., Trippl et al. 2020; Bugge, Andersen, and Steen 2021), but it is also evident that start-up and incumbent activities take place where the respective other is less dominant, indicating the influence of other/non-green regional determinants (e.g., Colombelli and Quatraro 2019; van den Berge, Weterings, and Alkemade 2019). In sum, our descriptive analysis does not lend support for the second hypothesis. We do not observe that green transport start-ups are more likely to emerge in regions that are also specialised in eco-innovation transport incumbents. Only a few regions feature a specialisation in both green incumbents and green start-ups.

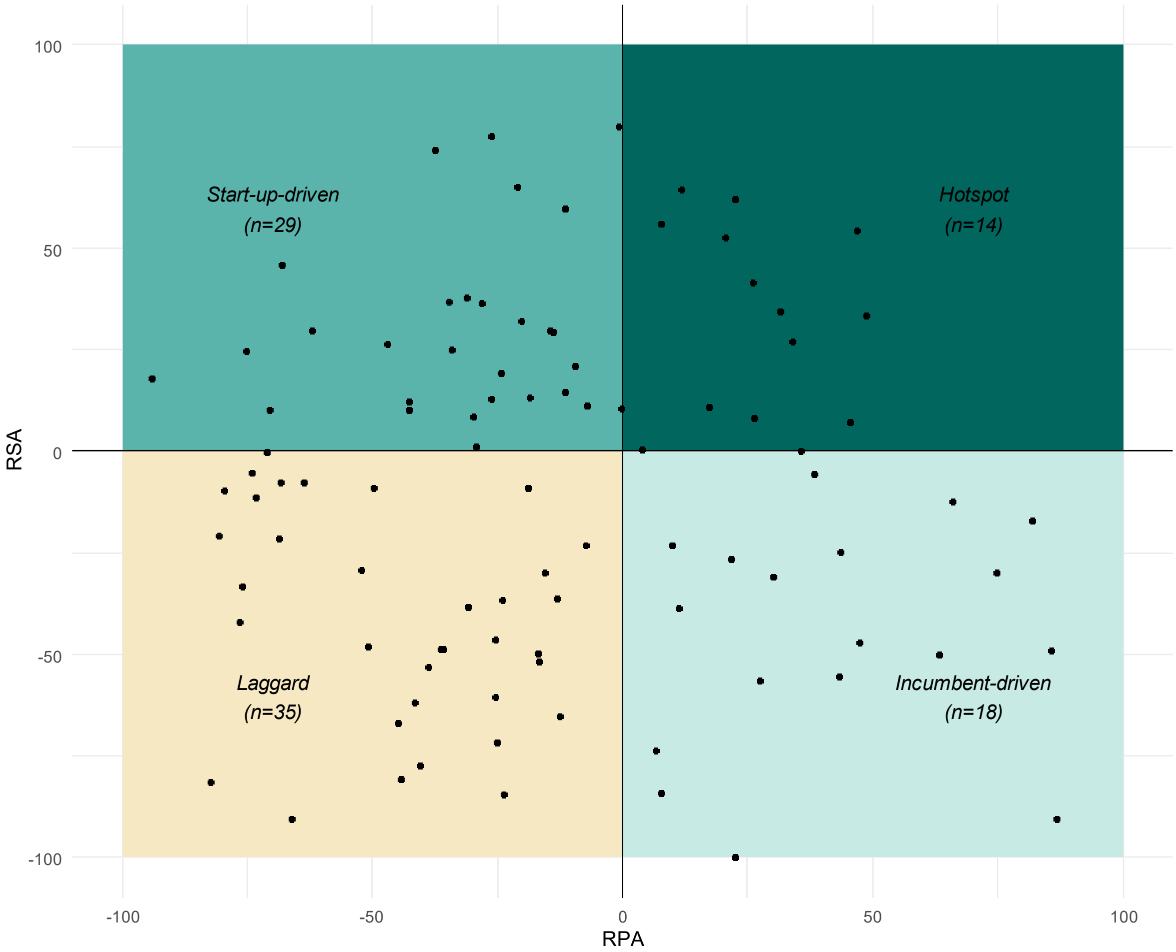

Figure 3: Regional typology according to eco-innovation actor specialisations in the transport sector in Germany (2009-2018)

Furthermore, Figure 4 shows that the different regional specialisations of eco-innovation actors can be found across Germany. At the same time, our results indicate that certain spatial clusters of the specific types of regions emerge. Green actor hotspots and start-up-driven regions predominate in the southern and eastern parts of the country. Consistently, lagging regions cluster in the centre and (north) west of Germany, while incumbent-driven regions seem to be evenly distributed. Interestingly, important locations of the automotive industry, such as Wolfsburg, Munich, Ingolstadt or Stuttgart, are mainly start-up driven or even regional hotspots of eco-innovative transport activities. This finding suggests that sectoral greening is also taking place in those regions that are characterised by strong industrial regime structures. The fact that hotspots rarely appear in isolation from start-up or incumbent regions could also indicate inter-regional spillover effects. Although some sparsely populated regions are considered actor hotspots, the geographical distribution seems to correlate with the population density in general. Accordingly, none of the depicted large cities has a below-average specialisation with both groups of actors.

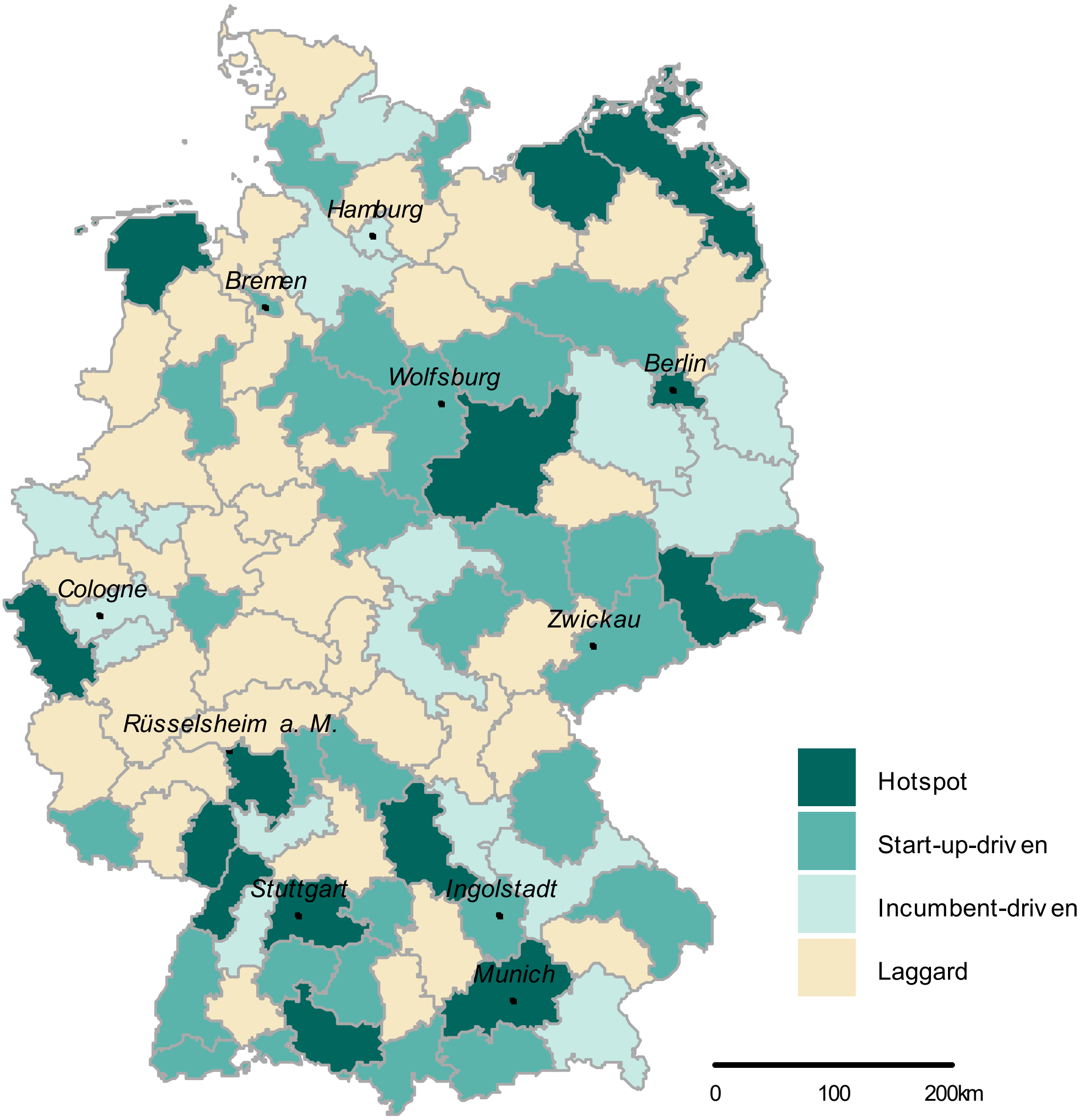

Figure 4: Region types of eco-innovation actor specialisations in the transport sector in Germany (2009-2018)

In order to better compare the regions, Table 4 provides descriptive statistics for several socio-economic indicators. In line with previous studies, we refer to key regional factors that have been shown to influence (green) innovation activities. These include, for example, the capital stock (GDP per capita), the population density to measure agglomeration externalities and the availability of high-skilled individuals measured as the share of employees with an academic background, i.e. tertiary education (e.g., Corradini 2019; Cojoianu et al. 2020; Coll-Martínez, Malia, and Renou-Maissant 2022). As a sector variable, we also consider the regional motorisation rate, which is calculated from the number of cars per 1,000 inhabitants.

In fact, the aforementioned finding seems to be confirmed, according to which regional hotspots of eco-innovators tend to be more urban, i.e. have on average a higher population density. Moreover, these regions have the comparatively highest GDP per capita, the largest share of highly qualified people and the fewest cars per inhabitant. These correlations are almost consistent across the different types of regions, with the exception of start-up driven regions that have on average fewer highly qualified people than incumbent regions and both the lowest GDP per capita and population density. These findings differ to some extent from previous studies, as start-ups seem to be particularly dependent on qualified personnel and profit from agglomeration effects (e.g., Giudici, Guerini, and Rossi-Lamastra 2019; Hoogendoorn, van der Zwan, and Thurik 2020; Horbach 2020).

Table 4: Mean values of socio-economic and sectoral characteristics by type of region

Type of region	N	Population per km²	GDP per capita (EUR)	High-skilled individuals (%)	Cars per 1,000 inhabitants
Hotspot	14	325	37,941	17.2	496
Start-up-driven	18	180	32,146	11.5	543
Incumbent-driven	29	285	35,194	13.5	514
Laggard	35	201	33,467	11.0	551
Total	**96**	**228**	**34,510**	**13.0**	**529**

Source: Calculations based on data provided by Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR INKAR database 2022)

6.5 Explaining differences in regions' green incumbent and start-up specialisations

In order to deepen and validate the descriptive results, we make use of econometric models. To this end, we predict the regional classification into the proposed typology (see Figure 3), with start-up and incumbent-driven regions each including hotspot regions (normalised RPA & RSA >0). Since laggard regions are inverse to green hotspots, we do not list them as a separate model. Therefore, three independent logistic panel regression models with robust standard errors clustered by regions are estimated, where the dependent variable is dichotomous and takes the value 1 if a region is classified into the respective type of actor in a given year, otherwise it takes the value 0. In order to avoid biases driven by little innovation activities and outliers, we have summed the start-up and patent counts for the corresponding year with the two previous years (moving window), resulting in a panel data set for the dependent variables covering the period 2011-2018. In addition, we use a one-year time lag[9] for the independent variables, which thus cover the years 2010-2017. The logistic regression models are given by:

$$\begin{aligned} \text{logit}\left(Type_{r,t}\right) = {} & \alpha + \beta_1 Population\ density_{r,t-1} + \beta_2 GDP\ per\ capita_{r,t-1} \\ & + \beta_3 High\text{-}skilled\ individuals_{r,t-1} + \beta_4 Car\ industry\ site_{r,t-1} \\ & + \beta_5 Large\ enterprises_{r,t-1} + \beta_6\ R\&D\text{-}intensive\ industries_{r,t-1} \\ & + \beta_7 Public\ transport_{r,2020} + \beta_8 Green\ votes_{r,t-1} + \theta_t + \varepsilon_r \end{aligned} \tag{2}$$

where the subscripts r and t denote the region and time period, θ_t is the dummy variable for each time window (time fixed effect) and ε is the error term. We include a number of common regional-level factors (see also Table 4): population density, GDP per capita and share of high-skilled individuals. Moreover, we include a region's share of large enterprises to proxy the influence of multi-national companies and a dummy variable indicating main locations of the automotive industry (headquarter of car manufacturers with more than 10,000 employees). The regional share of employees in research-intensive industries reflects technological capabilities, while a further dummy variable indicates whether the distance to the nearest public transport stop is above or below German average (values for 2020). The regional shares of votes for the political party "the Greens" in the 2009, 2013 and 2017 federal elections serve as a proxy for ecological ideals and lifestyles (e.g., Horbach 2020; Coll-Martínez, Malia, and Renou-Maissant 2022).[10] The detailed descriptions of the variables are included in the annex (Table A 4 in Appendix B).

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[9] The results are also robust when the explanatory variables are lagged by two or three years.

[10] Initially, we also controlled for the unemployment rate, median age, car density and public R&D expenditures. The variables, however, correlate strongly with GDP per capita, population density or high-skilled individuals.

Table 5 presents the regression results, with model (1) including hotspot regions as the dependent variable and models (2) and (3) including incumbent-driven and start-up-driven regions. Likelihood ratio tests indicate that all models are significantly better at explaining differences among the groups than intercept-only models. The models do not suffer from multicollinearity as indicated by correlations (see Table A 4 in Appendix B) and variance inflation factors (<5). We are aware that there might be minor problems with endogeneity for some variables, which are addressed by the use of time-lags and the implemented panel structure. However, we are careful with the interpretation of our regression results, not speaking about causalities but correlations. This is a common procedure in the pertinent literature (see, e.g., Horbach, Oltra, and Belin 2013). The main results presented below are robust to a number of changes in the econometric strategy. That is, results hold when using subsets of the original data set (e.g., excluding years/observations), when using other econometric specifications (e.g., probit models) and when using other thresholds for the dependent variables (e.g., normalised LQs > 10). We also checked for spatial autocorrelation, which is not an issue in our empirical setting.

In model (1), we find several statistically significant effects explaining that a region belongs to the group of eco-innovation hotspots rather than belonging to another type of actor specialisation. For instance, the regional human capital endowment affects the simultaneous regional specialisation in eco-innovation incumbents and start-ups. For a one percent increase in the share of highly-skilled individuals in a region, the change in the odds of a region being an eco-innovation hotspot compared to not being a hotspot is 1.338 ($e^{0.29}$, $p < 0.01$). This finding is also supported by the positive and significant effect of the share of employees working in knowledge and research-intensive industries (1.112, $e^{0.11}$, $p < 0.01$). Furthermore, we find that regions where important industry sites of big car manufacturers are located are more likely to be a hotspot for green transport innovations. The results show that the odds of being a regional eco-innovation hotspot are 1.997 ($e^{0.69}$, $p < 0.1$) times higher for regions that host large car manufacturers compared to those regions where the car industry is less active. This is remarkable, as regions characterised by strong related regime structures (automotive industry) may well be considered green hotspots, underlining the diverse influences of incumbent industrial structures. We also observe a negative effect of the regional GDP per capita on the likelihood that a region is an eco-innovation hotspot. However, this effect is negligible. While this seems counterintuitive at first, the effect might be driven by the fact that some hotspot regions are located in eastern Germany, which is generally lagging behind in economic performance. In that regard, it is important to bear in mind that our regional typology reflects specialisation patterns, not total regional innovation capacity. As for the remaining variables, the results point to the fact that the odds of being a hotspot compared to not being a hotspot are equal.

The main results for the importance of regional human capital also hold for models (2) and (3), which reflect green incumbent or start-up specialisations. Thus, hypothesis 3 finds partial support since hotspots and incumbents also benefit from high-skilled individuals. However, there are some peculiarities for eco-innovation incumbent and start-up specialisations as compared to regions being a hotspot. That is, regions are likely to be incumbent-driven as a function of population density, supporting our first hypothesis. This means that urban regions are more likely to have a specialisation in green incumbents, but this does not necessarily mean that these urban regions also host an above-average number of green start-ups. Another interesting finding relates to the share of large enterprises in a region. Our results point to the fact that an increase in the share of large enterprises in a given region decreases the odds of being a green incumbent-driven region (odds ratio 0.01, $e^{5.21}$, $p<0.05$) Although these regions show a specialisation in eco-innovation activities driven by incumbent firms, our results indicate that the share of large enterprises (incumbents) of all economic actors should not be too high in order to induce green innovation activities. Put simply, we find that regional eco-innovative change driven by incumbents is possible if the regional regime structures are weak, i.e. if large enterprises do not dominate the regional economy. We do not find such effects for regional specialisations in green start-ups.

In sum, it is interesting to note that many regional factors which are commonly studied in quantitative research on eco-innovation (e.g., green votes) do not seem to help us understand why some regions are characterised by either green start-ups, green incumbents, both or none. While our research clearly demonstrates that regions differ with respect to which actors drive eco-innovations and sustainable change, it is less helpful for understanding why they differ. This means that the different composition of eco-innovation actors in regions depends on other factors that we do not take into account in our model. These may include further regional factors such as (in) formal institutions, but also extra-regional factors and forces on other spatial scales, i.e. multi-scalar interdependencies. In any case, our findings suggest that the specialisation patterns of different actors are based on complex and latent interrelations that require in-depth analyses.

Table 5: Results of the logistic regression analyses

	Hotspot (1)	Incumbent-driven (2)	Start-up-driven (3)
Population density	0.0004 (0.0003)	0.002** (0.001)	-0.0001 (0.0003)
GDP per capita	-0.0001* (0.00004)	-0.0001* (0.00004)	-0.00003 (0.00003)
High-skilled individuals	0.291*** (0.069)	0.268*** (0.063)	0.146*** (0.044)
Car industry site	0.692* (0.384)	0.053 (0.583)	0.211 (0.357)
Large enterprises	-3.402 (3.343)	-5.069** (2.498)	-1.311 (2.110)
R&D-intensive industries	0.106*** (0.035)	0.076* (0.039)	0.074*** (0.024)
Public transport	0.116 (0.623)	-0.448 (0.452)	-0.295 (0.323)
Green votes	0.063 (0.079)	-0.007 (0.076)	0.049 (0.057)
Constant	-3.967*** (0.992)	-1.075 (0.834)	-1.377** (0.688)
Observations	768	768	768
Time fixed effects	Yes	Yes	Yes
Pseudo R^2 (McFadden)	0.200	0.155	0.045
Log Likelihood	-266.45	-426.42	-501.25
AIC	564.89	884.84	1034.5
LR Test	132.81*** (df=16)	155.9***(df=16)	47.498***(df=16)

Note:*p<0.1; **p<0.05; ***p<0.01; robust clustered standard errors in parentheses (clustering at the regional level)

6.6 Discussion

Previous studies which have analysed eco-innovation activities and green technology development at the regional level have consistently found that technological capabilities and the local knowledge pool, institutional framework conditions as well as market characteristics explain uneven spatial patterns of eco-innovation developments. While the regional determinants of eco-innovation emergence have thus been extensively studied (Losacker et al. 2021), the present study was designed to determine differences in regional specialisation with eco-innovators. By distinguishing between incumbents and newcomers (start-ups), we show that regions differ strongly in terms of the drivers of eco-innovation in the transport sector.

On a more descriptive level, the relative majority of German regions have both a below-average incumbent and start-up specialisation (laggard), while roughly 15 percent can be considered eco-innovation transport hotspots. At the same time, about half of the regions are dominated by either incumbents or start-ups. The regional specificity of actor specialisations supports recent research findings that point to the importance of both incumbents and start-ups and their simultaneous presence in eco-innovation development and regional transitions (e.g., Boschma et al. 2017; van den Berge, Weterings, and Alkemade 2019; Strambach and Pflitsch 2020). This is consistent with the finding that regions characterised by incumbent firms in the automotive industry are more likely to be a green transport hotspot.

At the same time, the spatial heterogeneity observed in our study highlights that theoretical assumptions about knowledge spillovers and the local emergence of novelty should not be generalised and require region-specific analyses. Although our descriptive analyses suggest that eco-innovation actor hotspots are more urban, which supports previous studies on green innovation (e.g., Giudici, Guerini, and Rossi-Lamastra 2019; Grillitsch and Hansen 2019), we do not find a significant relationship that hotspots occur per se more likely in urban areas. Since we explicitly do not look at the number of eco-innovations, but at their relative importance, our study shows a more nuanced picture. In other words, it should not be assumed that eco-innovation is only an urban phenomenon and or a phenomenon that an urban context alone can induce. Although we cannot control for country-specific effects, this seems to suggest that rural regions, which typically show a poor endowment of assets (Tödtling, Trippl, and Frangenheim 2020), may have specific chances to create eco-innovation activities and deviate from dominant regime pressures elsewhere. For future analysis, this suggests that we have to avoid an “urban bias” in the perception of which regions give impetus to sustainability transitions in the transport sector.

Another important finding is that the share of high-skilled individuals is a strong predictor of the regional actor specialisation. As the share of human capital endowment increases, the likelihood of regions specialising in either one or both types of actors increases as compared to laggard regions. These results indicate that eco-innovations, including technological, service-related and business model types of innovation, strongly depend on engaged (economic) actors. The same is evident from the positive correlation between the regional share of employees in knowledge-intensive industries and eco-innovation actor specialisations. This is in line with recent geographical research that stresses the importance of firm-level agency for green regional path development (e.g., Trippl et al. 2020). Accordingly, start-ups and incumbent firms can be key agents of change by modifying assets and thus contributing to path renewal and path diversification. As this usually requires favourable organisational support conditions and a strong regional knowledge base, high-skilled individuals are expected to significantly contribute to eco-innovation (Capasso et al. 2019).

By focusing on the transport sector, this paper departs from previous studies that either look at the entire green economy (e.g., Montresor and Quatraro 2020; Santoalha and Boschma 2021) or focus on selected industries or technologies (e.g., Bugge, Andersen, and Steen 2021; Gibbs and Jensen 2022). First, we feel that an explicit sectoral perspective is missing in most quantitative studies on eco-innovation, although there is a risk that developments in subsectors may become blurred and not be fully captured. In this context, Boschma et al. (2017) point out that different regime structures prevail in different types of regions, thereby creating region-specific opportunities for innovative and transformative processes. Yet, our approach provides a useful possibility to map and explain actor specialisations across different spatial contexts. Second, the comparison of incumbents and new entrants seems useful, as they are influenced by different logics and regional factors. At the same time, this approach also includes the possibility of considering actors outside the economic sphere, such as social or political actors. If the data allows, it is also conceivable to differentiate regionally according to the characteristics of the actors, the radicality of eco-innovations and by whom these particularly influential eco-innovations have been created. Here we should refer to studies that have already pursued promising approaches by, for example, including the amount of venture capital financing (e.g., Vedula, York, and Corbett 2019; Cojoianu et al. 2020). Third, despite the panel structure, the presented topology and analyses are rather static. A temporal perspective would additionally contribute to a better understanding of the links between the joint appearance of incumbents and start-ups. This would also clarify in which regions start-ups contribute to the realignment of established actors or, conversely, start-ups benefit from the greening of incumbents. Fourth, we rely on variables that reflect and explain the eco-innovation actor specialisations with certain limitations. Given the complexity of systemic factors influencing regional innovation and transition activities, there is still room for further progress in determining the causes of spatial differences. This also includes developments beyond the region, especially since global dynamics play a central role in the transport sector and mobility systems are usually integrated across regions (Tödtling, Trippl, and Desch 2022).

6.7 Conclusion

The present paper set out to analyse the regional specialisation of eco-innovation actors in the German transport sector, focusing on differences between new actors (start-ups) and established actors (incumbent firms). Against this background, we have developed a regional typology, which categorises regions according to their degree of specialisation. The typology distinguishes regions that specialise neither in green start-ups nor in green incumbents (laggard), that specialise in one of the two actor groups (start-up-driven, incumbent-driven), or that have a comparative advantage in both actor groups (hotspot). In a second step, we aimed at explaining regional differences in eco-innovation actor specialisations through statistical regression analyses by including a variety of regional determinants.

Our study provides two major contributions to the literature on eco-innovation and sustainability transitions in regional studies and economic geography. On the one hand, we demonstrate that regions are very heterogeneous in terms of their composition of relevant eco-innovators and that it is quite exceptional for a region to be equipped with both a green start-up ecosystem and innovative green incumbents. Unfortunately, these regional nuances are often neglected in the academic literature, which mostly focuses on general innovation capacities. On the other hand, our article supports previous findings that the human capital endowment significantly affect eco-innovation activities. While this seems also very relevant for the relative importance of eco-innovation actors, agglomeration effects can hardly be detected. Rather, it is critical that the appropriate (related) capabilities are available.

What remains challenging, however, is to explain the patterns in more detail, for which further research is needed. To develop a more comprehensive picture of actor-specialisations beyond the transport sector, additional studies should be undertaken to investigate technology and industry specificities across regions and countries. This also concerns questions of the extent to which start-ups and incumbents influence each other, how this relationship develops over time and what influence they have on broader transformational processes. For this purpose, micro data could be used to better detect, for example, spin-off activities, or to estimate the impact of the respective eco-innovation pathways. In addition to including a temporal perspective, the use of further data and other research methods, especially of a qualitative nature, is required to better grasp complex spatial patterns and underlying causes.

This would also bear practical implications in that an improved understanding of actor specialisations could contribute to more adequate policies. These are necessary for eco-innovative and transformative changes in and across regions. One of the main policy priorities should be to go beyond the technological and industrial specialisation of regions and better account for the regional variety in actor prevalence. In the European context, for example, existing Smart Specialisation policies could be complemented by a sensitivity to region-specific actor specialisations. Instead of focusing on absolute innovative and transformative activities, as has been the case in the past, it is becoming apparent that regions, regardless of their economic prosperity or centrality, have relative strengths and weaknesses in terms of eco-innovators. These need to be addressed by (regional) policy measures accordingly. Against this background, it seems reasonable that start-up-driven regions require other measures than incumbent-driven regions. Laggard regions should also consider which actors to promote in order to generate eco-innovations. Hotspot regions, on the other hand, which already offer good conditions, should aim to strengthen markets for their eco-innovations in other regions and promote synergies between start-ups and incumbents. Our typology is thus a promising first step that helps regions understand how they compare to other regions and which local actors are particularly influential in driving eco-innovation needed for sustainability transitions.

7 Regional Eco-Innovation Trajectories

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Abstract

Given that eco-innovations and the associated renewal of regional economic structures are pivotal in addressing environmental challenges, regional 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 paper sheds light on how eco-innovation activities unfold in different regional contexts. For this purpose, we introduce social sequence analysis methods into the research toolkit of research on regional development. These novel methods allow us to understand to what extent regions engage in eco-innovation activities, how these activities change over time and to what extent similar or unique eco-innovation trajectories (co)evolve. Based on this empirical approach, we distinguish different types of regional eco-innovation trajectories and find a strong persistence and path dependency of green regional development.

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7.1 Introduction

The exploration of regional innovation and industry dynamics has been among the main interests of evolutionary approaches in economic geography. There is a consensus that both established and new regional trajectories to a large extent build on local preconditions, particularly emphasising 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 (Martin and Sunley 2006; Boschma and Frenken 2011; Henning 2018). More recently, evolutionary studies have also devoted specific attention to developing green industries and green technologies, as these hold the promise of both creating economic benefits and reducing environmental burdens (Tanner 2016; MacKinnon, Dawley, Steen, et al. 2019; Gibbs and Jensen 2022).

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; Morales and Dahlström 2023). 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 organisational and institutional configurations (Dawley 2014; Martin and Coenen 2015; Steen and Hansen 2018; MacKinnon, Dawley, Steen, et al. 2019; Sotarauta et al. 2021). This broader understanding of green regional development has also increasingly resulted in studies complementing evolutionary perspectives with systemic ones, 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 emphasised, albeit implicitly, scholarly debates suffer from the lack of insights on regions' long-term stability and change in green innovative activities beyond individual industries or technologies.

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 between the relative importance of incumbents and newcomers using specialisation measures. Second, our contribution traces eco-innovation specialisation for the 401 German NUTS-3 regions over the period of 1997-2018, which ensures spatial granularity and a long-term perspective. Third, we advance regional studies' 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, characterise and compare different types of regional pathways. As such, this empirical approach provides advanced empirical insights into 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 summarises 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 specialisations measures and social sequence analysis. The section presenting the results 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.

7.2 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 2011; Dawley 2014). Originating from evolutionary economics and its core hypothesis of the inheritance of organisational routines (see Nelson and Winter 1982), evolutionary economic geography (EEG) emphasises 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 (Tanner 2014; Santoalha and Boschma 2021). Complementary institutional, actor-specific and political interdependencies ultimately lead to persistent path and place dependent processes associated with gradual changes (Martin and Coenen 2015; Binz, Truffer, and Coenen 2016; MacKinnon, Dawley, Steen, et al. 2019; Sjøtun and Njøs 2019; Jakobsen et al. 2022). Recently, substantial progress has 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, assuming that their development is highly path dependent.

7.2.1 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 in shaping institutional frameworks that crucially influence green path development (Sotarauta et al. 2021; Gibbs and Jensen 2022; Morales and Dahlström 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 unfavourable 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 present 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 behaviour, characterised by strong vested interest, as structures were already shaped accordingly in earlier regional path development processes (Steen and Hansen 2018; MacKinnon, Dawley, Steen, 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 green industries in specific regions. Consequently, a generalisation 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.

7.2.2 Types of green regional development

Within regional studies 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 organisational 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 their own governance capacities, allowing them to exert immediate influence on innovation activities (Cooke 1992; 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[11] that are necessary for the greening of regional economies. Overall, they claim that green industrial development differs between peripheral (1), green specialised (2), dirty specialised (3), as well as metropolitan regions (4). Although the

[11] 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).

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 characterisation in a stylised 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; Morales and Dahlström 2023). 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 organisational support measures. Opportunities for green path development are therefore 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; Calignano, Fitjar, and Hjertvikrem 2019; Grillitsch and Hansen 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 specialisation in a green industry (2) usually have favourable 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 specialised 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 specialisations (Grillitsch and Hansen 2019; Sjøtun and Njøs 2019).

On the other hand, some regions have specialised in dirty industries (3), for example coal and oil. This type of region is particularly characterised by the competition between established industrial paths and emerging green activities. As with green-specialised regions, there is the challenge of potential lock-ins manifesting themselves 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 characterised by pluralistic behaviour, 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 organisations, 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. They 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.

7.3 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.

7.3.1 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 limitations of proxy variables 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 to identify green start-ups.

In this study, patent information was retrieved from OECD's REGPAT database. It regionalises all patent applications filed to the European Patent Office (EPO) as well as those filed internationally under the Patent Co-operation Treaty (PCT) from 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 (Tanner 2014; van den Berge, Weterings, and Alkemade 2019). The choice of NUTS-3 regions is a result of both data availability and the ambition of analysing 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). We, therefore, rely on the Mannheim Enterprise Panel (MUP) of the Centre for European Economic Research (ZEW) to identify company foundations that can be considered green. 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). For this study the companies' addresses, year of foundation, economic sector and activity descriptions are of particular importance. 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. Following Rammer et al. (2023), 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 A 5 in the Appendix C 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 (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.

7.3.2 Green incumbent and green start-up specialisations 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 advantages in these different eco-innovation activities over time. The relative importance of both green incumbents and green start-ups help 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 normalised between -100 and 100, with positive values reflecting above-average green specialisations of regions. We calculate:

$$RPA_{rgt} = 100 \times \tanh \ln \left[\frac{Patents_{rgt} / \sum_r Patents_{rgt}}{Patents_{rt} / \sum_r Patents_{rt}} \right] \quad (3a)$$

$$RSA_{rgt} = 100 \times \tanh \ln \left[\frac{Start\text{-}ups_{rgt} / \sum_r Start\text{-}ups_{rgt}}{Start\text{-}ups_{rt} / \sum_r Start\text{-}ups_{rt}} \right] \quad (3b)$$

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 specialisation with eco-innovation actors, we derive four different types of regions (see Table 6). Accordingly, green specialised regions are those that are specialised in both types of actors. In contrast, green start-up and green incumbent specialised regions are characterised by an above-average specialisation in either of the respective two dimensions, while non-specialised regions show a below-average specialisation 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 6: Dimensions of regional eco-innovation specialisation

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

7.3.3 Social Sequence Analysis

From an evolutionary perspective, it seems very promising to analyse 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 specialisation dominates? To what extent do regional developments resemble each other?

A diverse set of methods that lends itself precisely to this research interest is social sequence analysis. First used in biology to compare and analyse 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 centre 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:

$$x = (x_1, x_2, \dots, x_l), \qquad with\ x_j \in A \tag{4}$$

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 specialisation dimensions, i.e. specialised/non-specialised 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 sequence analyses contribute, on the one hand, to revealing the uniqueness of green regional trajectories resulting from the specific duration and arrangement of green actor specialisations. 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 analyse 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[12] 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 allows a more holistic view on green actor specialisations over time.

[12] 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).

7.4 Results

The results section is structured along three main analytical steps. First, we provide an overview of the regional specialisations 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 characterise the identified types by means of socio-economic data.

7.4.1 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 specialisation and the corresponding assignment to one of the four types of specialisation (see Table 6), sequence analysis methods help to make these cross-sectional distributions comparable through visualisation 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 specialisations of a specific region. These index plots are shown in Figure 5, distinguishing between unsorted sequences (left) and sequences sorted by start and end (centre and right).

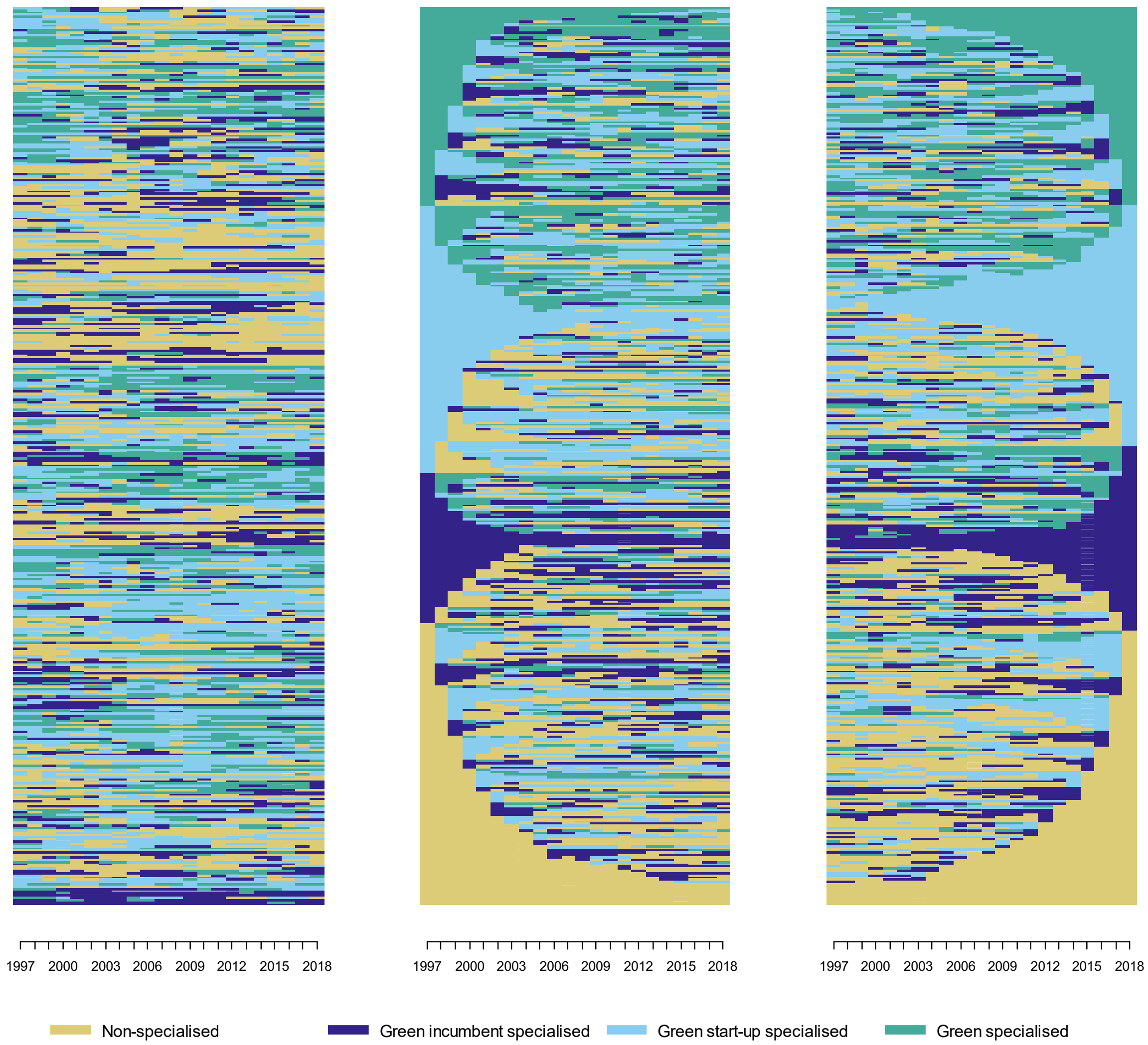

Figure 5: Region-specific eco-innovation specialisations over time

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. Only 14 of the 401 regional pathways are identical (about 3.5 percent). Most of these are regions that show no specialisation over the entire period. At first glance, the diversity of regional development patterns does not seem surprising given a total number of around 8,800 states, each with four possible types of specialisation. 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 specialisation, which would suggest that regional patterns converge. 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 specialisation or green start-up specialisations, while about 20 percent of the regions are green incumbent or green specialised. The mean time of specialisation supports these findings. Over the whole observation period, regions have been non-specialised as well as start-up specialised for an average of seven years, while an incumbent and green specialisation averages only four to five years (see Figure A 1 in Appendix C).

When sorting regions by start and end state, their unique pathways can be traced more clearly (see again Figure 5). One of the most characteristic patterns is that there are hardly any transition from a previously non-specialisation to a green specialisation and vice versa. Rather, regions that were originally driven by green start-ups or green incumbents specialise differently, with a larger proportion remaining non-specialised. Conversely, non-specialised regions remain stable or eventually becoming dominated by only one of the two types of actors. Regions that become green specialised over time are often previously green start-up specialised. 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 visualisation require complementary analyses.

7.4.2 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 and detecting similarities of regional eco-innovation trajectories. As explained in section 7.3.3, cluster analyses allow to delineate distinct types of regions given their development of eco-innovation specialisation. Overall, we identify six distinct types of regions using optimal matching techniques based on a Ward algorithm (see Figure 6). While four types have stable trajectories that essentially correspond to the aforementioned specialisation dimensions, some regions in fact develop green specialisations 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 specialised 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

specialisation, which occur irregularly, this type of region shows almost no specialisation at all. Consistently, specialisation with both types of actors is less likely.

"Green start-up regions" are those in which green start-up but no incumbent specialisations 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 specialised is in line with their higher relative frequency (see again Figure A 1 in Appendix C). Over the years, only individual deviations can be observed in this trajectory, with the other three specialisations occurring with roughly the same intensity.

Regions that follow a non-specialised trajectory are the most common (roughly 29 percent). As can be anticipated from Figure 5, this type of region only deviates, if at all, into green start-up or incumbent specialisation. Overall, the development of "non-specialised 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-specialised. Apart from a few years with green start-up or incumbent specialisation, regions of this trajectory are characterised by green activities from both established and new actors. In contrast to green incumbent and green start-up trajectories, where a below-average specialisation 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 specialisation (n=29) and, on the other hand, regions whose greening results from an earlier green start-up specialisation (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., Colombelli and Quatraro 2019; Corradini 2019) or, vice versa, from green start-ups and newcomers who trigger change of established actors (e.g., Dewald and Achternbosch 2016). 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 characterised by fluctuations in specialisation. Instead of being non-specialised, a change to the other type of main green actor can be observed more frequently. In recent years, however, these regions seem to have stabilised in eco-innovation activities of both actor groups at an above-average rate.

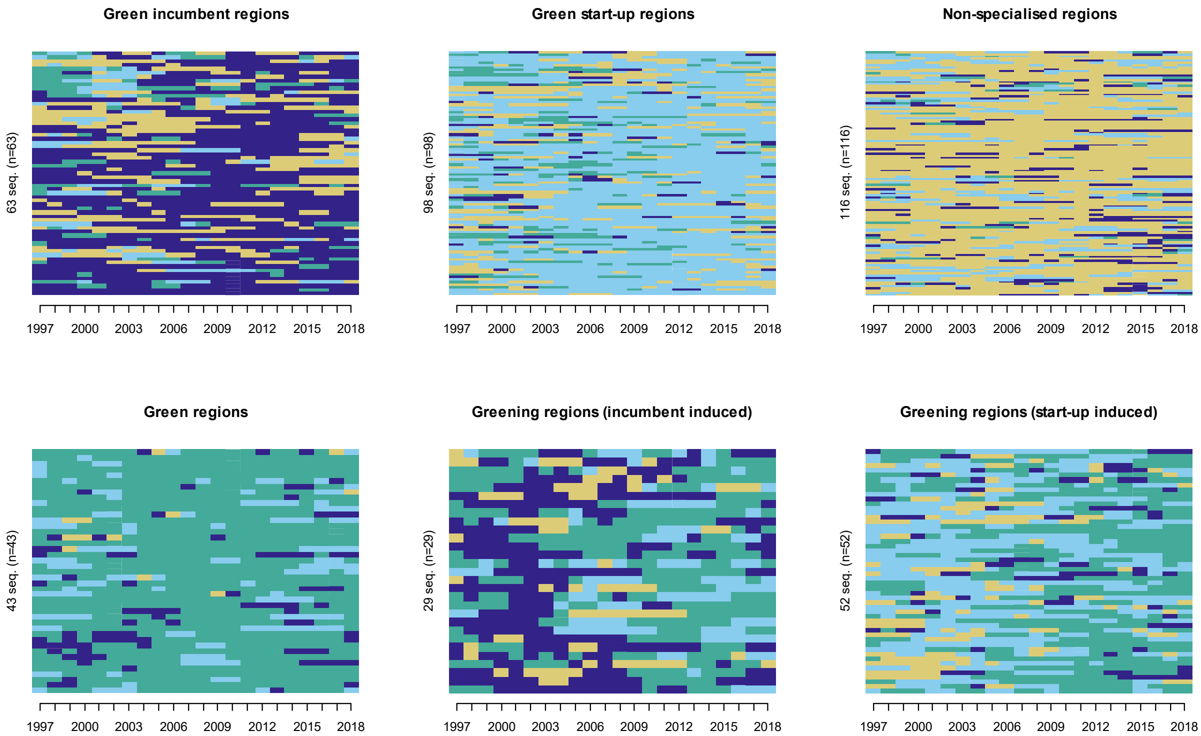

Figure 6: Different types of regional eco-innovation trajectories

By mapping the types of regional eco-innovation trajectories, we are able to reveal further characteristics beyond the temporal development (see Figure 7). Particularly the differences between the northeast and southwest stands out from the geographical distribution in eco-innovation specialisations. 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-specialised. In contrast, green start-up and green incumbent regions are spread across the country, with the latter appearing to be more urban. 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 specialisation and thus cannot be classified as green-specialised. Given that start-ups usually benefit from agglomeration advantages, this result appears 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 specialisation over the years, both incumbent and start-up-induced, are again more likely to be found in rural regions of the south and east.

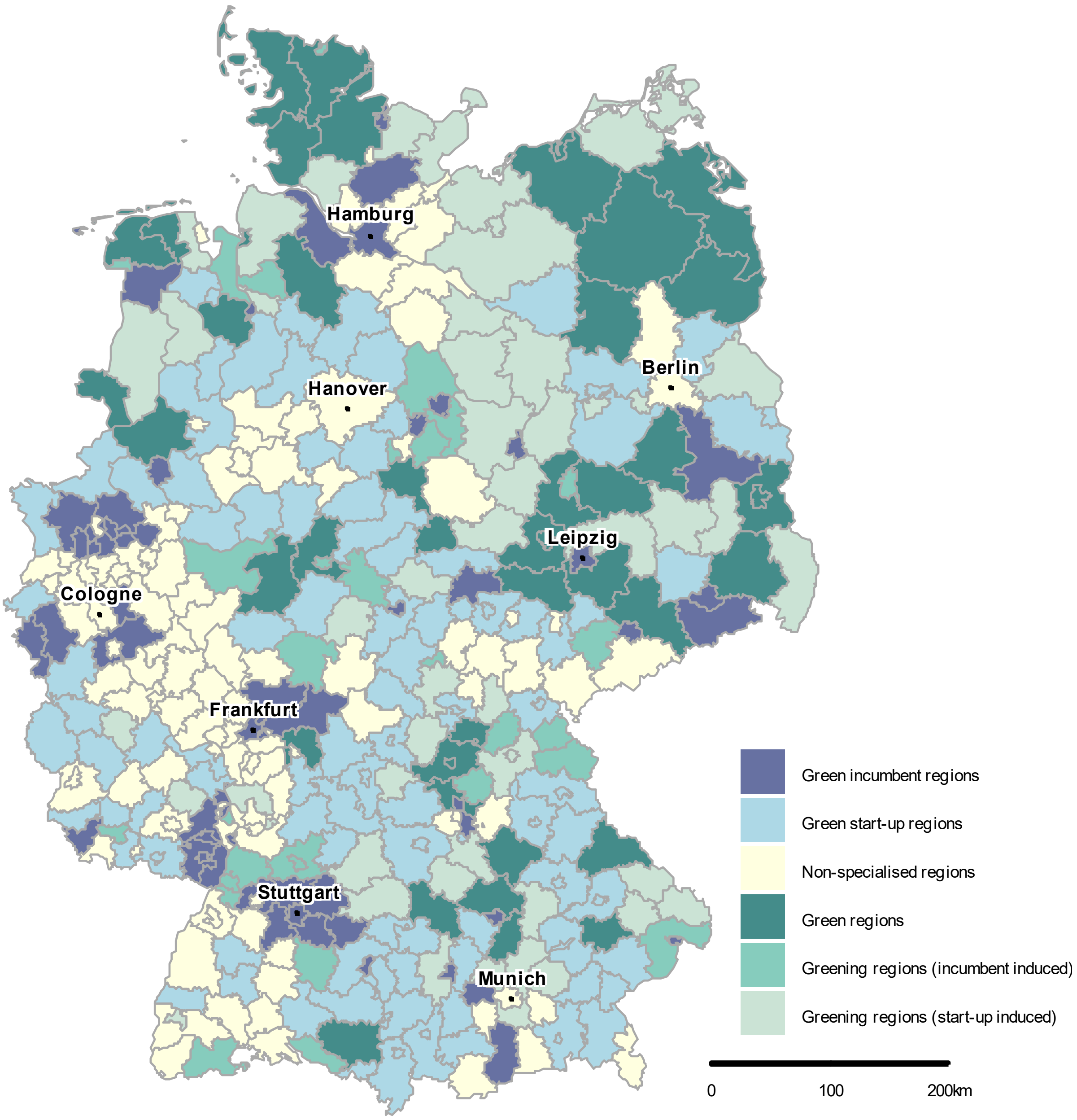

Figure 7: Geographical distribution of the different types of eco-innovation trajectories

In line with the spatial distribution of the individual eco-innovation trajectories, it is noticeable that neighbouring 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-specialised regions between Cologne and Frankfurt, and start-up regions on a central north-south axis. To control for spatial autocorrelation, we follow González-Leonardo, Newsham, and Rowe (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 A 6 Table in appendix C). 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-specialised 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 green 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 (1970, 42) fundamental law that "everything is related to everything else, but near things are more related than distant things".

To further validate the spatio-temporal patterns of regional eco-innovation specialisations, in a final step we aim to characterise 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 provide an in-depth discussion of these trajectory-specific statistics in the online appendix.

7.5 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 it is usually done in case study designs. As such, we employ a broader approach that allows to identify differences and commonalities in green activities across multiple regions. Methodologically, we enrich economic geography research by introducing and applying sequence analysis methods. By 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 mainly unfolds heterogeneously among regions. Instead of unique development patterns, a multitude of annual fluctuations in specialisations is 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 specialisation, however, the proportion of regions with a green start-up specialisation or no specialisation 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 specialisation.

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 specialisation 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. 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-specialised trajectories hardly show any green specialisation 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 specialisation can only be identified for one fifth of the regions. This greening results from a previous specialisation by 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 (Tanner 2014; MacKinnon, Dawley, Steen, et al. 2019; Santoalha and Boschma 2021).

Third, in a similar vein, our results indicate trajectory-specific spatial patterns. We find that neighbouring 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-specialised 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-specialised 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, which is supported by 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 allows to characterise 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 specialisation 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 below average economic prosperity (cf. GDP in Figure A 2 in Appendix C) 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 specialisations 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; Morales and Dahlström 2023). The influence of dirty industries also remains rather vague. However, exemplary reference can be made to historical coal regions, such as the Ruhr area, which have obviously managed to pursue green innovation activities through established actors. Accordingly, dirty specialisation does not need to be an obstacle, although green start-up activities are less evident, suggesting certain lock-in effects.

7.6 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 generalisable 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 having a focus on 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 specialisation patterns over the entire period, manifested in trajectories with no specialisation, 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 neighbouring 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 has also certain limits. 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). In order 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 specialisations of regions remain vague. For example, a green specialised region may potentially contribute little to sustainable change, while conversely, non-specialised 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 be useful to 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 unfavourable specialisation patterns, we feel that sustainability challenges can be addressed in a more sophisticated way.

PART THREE: CONCLUSIONS

8 Summary and main contributions

Drawing on insights from geographical innovation and transition studies, the main purpose of this dissertation was to reveal regionally nuanced perspectives on eco-innovation activities of incumbents and start-ups. The hitherto neglected view on regional actor specialisations is believed to enrich the broader geographical eco-innovation literature, with the main findings and contributions summarised below.

To start with, the dissertation aimed at systematically reviewing the geographical literature oscillating between the two research directions on eco-innovation emergence and their relevance for broader socio-technical transitions (*Research Objective 1*). The systematic review of more than 230 research articles (see also Table A 2 in Appendix A) suggests that the literature consider distinctive aspects of inquiry on actors, institutions and technologies. Notwithstanding their conceptual, methodological and empirical particularities, the research directions are not fundamentally opposed, but complement each other. In this regard, integrative research efforts are needed that focus on place specificities in the diversity, roles and agency of actors, rather than seeing them solely as enablers of eco-innovation activities (innovation studies) or following an overly simplistic distinction between niche and regime actors (transition studies). In addition, eco-innovation activities are to a large extent enhanced or impeded by formal and informal institutions. A more sophisticated geographical understanding therefore requires the consideration of institutions both as regional contextual factors and in relation to specific technologies and sectors. There is also still potential for greater convergence in reconciling innovation studies' focus on regional endogenous technological capabilities and knowledge bases with transition studies' emphasis on sector-specific interdependencies across spatial scales. This dissertation has been one of the first to outline in a systematic way promising avenues for a deeper integration of the two fields of research. In doing so, it responds to recent calls for cross-fertilisation (e.g., Binz et al. 2020) with the ambition of gaining a better understanding of the geography of eco-innovation emergence and application.

Well aware of the difficulty of adequately addressing all the aspects mentioned above, this dissertation has focused particularly on the actor dimension. More precisely, the aim was to assess the extent to which regions specialise in eco-innovation activities of incumbents and start-ups (*Research Objective 2*). By investigating green patenting and green start-up activities in the German transport sector, this dissertation has identified different types of regions with regard to eco-innovation actor specialisations. That is to say, many regions show no specialisation at all, while others are dominated by only one type of actor. In addition, only a few regions are specialised in both green incumbents and green start-ups. Overall, this regional heterogeneity seems to moderate to some extent theoretical assumptions in the literatures: that eco-innovation activities of incumbents and start-ups are mutually dependent vis-à-vis those that green start-ups emerge largely detached from incumbent actor structures. In a second step, logistic regression analyses were carried out to explain differences in regions' green incumbent and green start-up-specialisations. The econometric results indicate a strong positive correlation between the regional human capital endowment, i.e. employees with an academic degree, and the relative importance of both types of eco-innovation actors. In contrast, there do not seem to be pronounced differences between rural and urban areas, partly contradicting previous research on absolute innovation activities, where bigger cities are usually considered hotspots.

In view of the foregoing, the final purpose of this dissertation was to explore the development of regional eco-innovation specialisations in incumbents and start-ups from a long-term perspective (*Research Objective 3*). To this end, social sequence analysis methods have been introduced into the research field to trace how eco-innovation activities unfold in regions and to reveal characteristic patterns of these eco-innovation trajectories across regions. To obtain a comprehensive understanding of green regional development, the focus was on general eco-innovation activities beyond specific industries or sectors. Therefore, patent and start-up data refer to innovation activities of the entire green economy. In essence, this evolutionary approach corroborates the regional heterogeneity in eco-innovation specialisations, while it also uncovers that these patterns seem to be very stable over time. That is, the majority of regions are permanently specialised in either green incumbents, green start-ups, both types of actors or none of them. In contrast, only a few regions develop an above-average eco-innovation specialisation in both green incumbents and green start-ups over time. It is noteworthy that this greening emerges from a previous specialisation in either green start-ups or green incumbents and not from scratch, i.e. no specialisation. Overall, it appears that neighbouring regions display similar eco-innovation trajectories, with regions that are (becoming) specialised in both green incumbents and green start-ups being more rural on average. The latter shows once again that urban-rural divides in innovation activities need to be considered in a more nuanced way. Being one of the first studies to use sequence analytical approaches in economic geography, another main contribution of this analysis is that it adds empirical insights to the discipline's theoretical assumptions about the persistent and path-dependent nature of regional development (e.g., Boschma and Frenken 2006; Trippl et al. 2020).

On a final note, the contribution of this dissertation is more than the sum of its parts. The review of the broader geographical literature on eco-innovative and transformative change, inter alia, provides a comprehensive yet largely neglected perspective on the role of diverse actors in eco-innovation activities. Against this background, the empirical parts of this dissertation focus on regional specialisations in eco-innovation activities of incumbents and start-ups. Sectoral and rather static analyses at the level of German labour market regions are complemented by general eco-innovation activities and dynamic perspectives at the level of German NUTS-3 regions. It is therefore useful not only to look at the articles individually; rather, the synthesis of the dissertation articles helps to provide a comprehensive picture of the importance of eco-innovation actors.

9 Limitations

This dissertation provides important insights into the geography of eco-innovation activities in general and regional perspectives on established and novel eco-innovation actors in particular. At the same time, it is indisputable that the research contributions are accompanied by a number of limitations, both in terms of data and methods as well as broader implications of the findings.

First, patent and company data are often used as proxies for (eco-)innovation activities, which inevitably leads to biased analyses. Beyond the much-discussed applicability of these data, given sector and industry specificities or different ways of protecting and exploiting innovative products and processes (Hoogendoorn, van der Zwan, and Thurik 2020; Mezzanotti and Simcoe 2023), the direct relation to eco-innovation actors might not seem straightforward. That is, simplifying assumptions were made that the environmentally friendly activities of incumbents are reflected in patents and those of start-ups in their corporate purpose. While this appears to apply at large, the research in this dissertation did not evaluate whether green start-ups actually also file patents, nor to what extent start-ups have emerged from existing companies (spin-offs). The assumed duality of green incumbents and green start-ups is therefore somewhat diluted, quite apart from the normative debates about what "green" actually means. Furthermore, the data predominantly reflect firm-level eco-innovation activities. The two empirical studies are thus limited by the lack of information on eco-innovative activities of multiple, non-firm actors such as research institutions, policy actors and intermediaries (e.g., Quatraro and Scandura 2019; Trippl et al. 2020).

Second, some weaknesses emerge from the employed methodological approaches. Despite a structured and transparent approach, selection bias and skewed sampling could have occurred in the systematic scoping of the geographical research on eco-innovations and sustainability transitions (paper one). This is particularly due to subjectivity in structuring the research, selecting relevant search terms and ultimately deciding which literature to include and which to exclude (Tranfield, Denyer, and Smart 2003; Snyder 2019). It therefore goes without saying that the literature review is subject to certain boundaries of analysis (Zolfagharian et al. 2019). Apart from that, the analyses of regional specialisations in eco-innovation actors are also accompanied by limitations. While the rather explorative analyses on the relative importance of eco-innovation activities of incumbents and start-ups offer valuable insights into general (long-term) development patterns, this dissertation did not evaluate their underlying mechanisms. Although regression analyses provide some explanations for spatial specialisation patterns (cf. Section 6.5), there are deficits in adequately capturing the complexity of eco-innovative change in regions, especially given the lack of appropriate data on institutional and political framework conditions as well as multi-scalar interdependencies.

Third, there is the question of the results' generalisability and explanatory power. One could certainly ask whether the insights also apply to regular innovation activities, to specific green industries or green technologies and one could ask whether they also hold true in other spatial contexts beyond the German case. Since the dissertation was limited to a focus on the relative importance of eco-innovation actors, it is also not possible to make valid assertions about the actual progress towards environmental sustainability. Put differently, the comparison with the German average alone does not give sufficient information on the overall intensity of eco-innovation activities. Against this background, it should be kept in mind that it is beyond the scope of this dissertation to allude on the economic and ecological impacts of eco-innovation activities. It is therefore unknown to what extent regional eco-innovation activities contribute to the reduction of environmental burdens (Rennings 2000) and how these activities relate to the economic development of regions more generally.

10 Implications for innovation policy

The importance of policy action and governance approaches to stimulate innovation has long been recognised. Over the past decades, however, different rationales have emerged to legitimise innovation policy interventions. These are often attributed to arguments about market failures (e.g., underinvestment in R&D) and systemic failures (e.g., lack of cooperation and coordination). Against the background of grand societal challenges, targeting complex transformational failures (e.g., overexploitation of natural resources) is also increasingly on the innovation policy agenda. Ideally, the different policy paradigms complement rather than replace each other (Weber and Rohracher 2012; Schot and Steinmueller 2018; Bours, Wanzenböck, and Frenken 2022). It is therefore hardly surprising that the development and diffusion of eco-innovation aimed at transformative change requires a plethora of policy instruments and strategies, i.e. policy mixes, at different spatial levels (Coenen, Hansen, and Rekers 2015; Kern, Rogge, and Howlett 2019). However, given large spatial differences in (eco-)innovation activities, policy approaches need to be adapted to place-specific conditions (Jakobsen et al. 2022; Tödtling, Trippl, and Desch 2022).

In accordance with the aforementioned, the results of this dissertation provide important additional implications for regionally sensitive innovation and environmental policies. While the literature review reveals general insights into the importance of regional innovation policies and regulation (cf. Section 5.4.2), it also suggests that policy-making would benefit from considering complementary aspects of the two broader geographical research directions. In particular, policymakers should strengthen eco-innovation activities by addressing both the demand and supply side (Uyarra, Ribeiro, and Dale-Clough 2019; Tödtling, Trippl, and Frangenheim 2020) as well as interdependencies between sectors within and across spatial scales (Steen, Faller, and Ullern 2019; Njøs et al. 2020).

Beyond these overarching policy recommendations, the findings on regional specialisations in established and novel eco-innovation actors suggest several options for policy action. As shown in this dissertation, regions seem to be far more heterogeneous in their composition of eco-innovators than often assumed, calling for adapted place-based measures to foster eco-innovation activities. So far, innovation policy has largely lacked specific instruments that tie in with the regions' relative importance in certain types of actors. Although there is actor-specific policy support, for example (green) start-up funding from governments (Cojoianu et al. 2020), innovation-based regional development mostly targets technological capabilities and sectoral structures. A prime example of this is the smart specialisation strategy for research and innovation (RIS3) to harness potentials for regional diversification in Europe (Piirainen, Tanner, and Alkærsig 2017; Montresor and Quatraro 2020). Given the increasing linkages between sustainability issues and smart specialisation strategies (McCann and Soete 2020) it seems beneficial to also take greater account of regional actor specialisations in eco-innovation activities. This implies avoiding a simplistic dichotomy between lagging and leading innovation regions, but considering regional strengths and weaknesses in green incumbents and green start-ups. Information on regional eco-innovation specialisations can be used to develop targeted measures aimed at simultaneously incentivising both types of actors and linkages between them, rather than focusing on either incumbents or start-ups (Hockerts and Wüstenhagen 2010). Additionally, this would help to foster different types of eco-innovations - ranging from technological to business model innovation - that are needed for transformative change.

From a spatio-temporal perspective, the results also suggest that many regions are permanently specialised in eco-innovation activities by either incumbents, new entrants or the lack of both. For these regions, another key policy priority should be to create incentives for the respective missing eco-innovator to unleash potentials for greener transition trajectories. As this dissertation focuses on the German context, regional specialisations trajectories could be more strongly considered in existing innovation and research policy initiatives at the national and federal state level, such as instruments of (green) start-up funding and innovation support of SMEs (Federal Ministry of Education and Research 2023). Overall, overcoming biased actor structures is particularly important to prevent negative regional lock-ins that could lead to less dynamic regional development, institutional inertia and few new (green) economic activities (Grillitsch and Hansen 2019; Tödtling, Trippl, and Frangenheim 2020). This also requires better support for interregional networking activities and an alignment of innovation policies of neighbouring regions, as these often display similar eco-innovation trajectories. Thus, the focus on regional actor specialisations is seen as an important innovation policy option to respond to path-dependent development patterns and accelerate the shift towards eco-innovation activities in regions.

That being said, a few general remarks remain on the role of (innovation) policy in the face of increasing environmental challenges. As mentioned at the outset, enormous and rapid global efforts are needed to combat global warming, biodiversity loss and the depletion of natural resources. This urgency also stems from insufficient policy action in the past (Andersen et al. 2023). From a geographical point of view, it is therefore indispensable that policy interventions are undertaken and coordinated at all spatial levels. Comprehensive and directed support through various policies at the (supra)national level, such as carbon pricing as well as eco-innovation and research subsidies (Jaffe, Newell, and Stavins 2005; Acemoglu et al. 2012), need to be complemented by place-based innovation policies (Magro and Wilson 2019). For the latter, this dissertation provides additional arguments, well aware that these are only one possible building block of policy mixes to address various failures and enhance regional eco-innovation activities for transformative change.

11 Future research

In recent years, a growing but fragmented body of literature has shed light on complex geographical realities of eco-innovations and their relevance for transitions towards environmental sustainability. While each of the two main research directions is characterised by specific research foci and interests - ranging from regional perspectives on eco-innovation emergence to multi-scalar interdependencies of transformative change - there is a lack of deeper integration of both. In this regard, the systematic literature review provides complementary insights into the systemic elements of actors, institutions and technologies that yield numerous untapped potentials for greater convergence in the future. Having said that, geographical work is also encouraged to more strongly consider theoretical, methodological and empirical specificities of the respective other direction of research. This does not mean, however, that the research streams should be combined on all accounts, which would be rather artificial, but that a comprehensive picture on the geography of eco-innovation activities only emerges from their synthesis (see also Losacker et al. 2023).

This dissertation, with its focus on regional specialisations in green incumbents and green start-ups, has provided a new inroad for such cross-fertilisation. While the findings reveal to what extent regions specialise in established and new eco-innovation actors (over time), the exact reasons and mechanisms behind these patterns remain to be elucidated. Broadly speaking, the rather exploratory and descriptive efforts of this dissertation should be complemented by qualitative research designs that are considered particularly helpful in explaining regional specialisation patterns. In addition, greater accuracy is needed in capturing the impacts of regional eco-innovation specialisations on transformative change. This could be achieved, for example, through a stronger focus on both disruptive eco-innovations, as measured by patent citations or start-up funding (Barbieri, Marzucchi, and Rizzo 2020; Cojoianu et al. 2020), and the diffusion of eco-innovations, which gives indications for their application (Bento and Fontes 2015; Losacker, Horbach, and Liefner 2023). Against this background, future studies also need to put more emphasis on interdependencies between regions, as their specialisations in eco-innovations do seem to be related. In a similar vein, several questions remain to be answered with regard to the different types of regions. Obviously, differences in eco-innovation specialisations between urban and rural as well as economically strong and weak regions seem to be less pronounced, which could be usefully explored in further research.

Finally, this dissertation also opens up new research possibilities in terms of data and methods. In order to improve the understanding of the geography of (eco-) innovation, great potential is seen in the combination of patent and company data, also taking into account recent advances in alternative data sources such as web-based approaches (Abbasiharofteh et al. 2023; Kriesch 2023). Methodologically, this dissertation has showcased the applicability of sequence analysis methods in economic geography, which will hopefully become an integral part of the discipline's research toolkit in the near future. A greater appreciation of the importance of spatio-temporal dynamics is considered an essential and necessary geographical research avenue, particularly in the context of innovation-based transitions towards environmental sustainability.

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Appendices

Appendix A

Table A 1: Search terms used by research stream and database

	Scopus	Web of Science
Geography of eco-innovations	TITLE-ABS-KEY (("eco-innovation" OR "environmental innovation" OR "sustainab* innovation" OR ((clean-tech OR cleantech) PRE/0 (innovation OR industr* OR sector OR "start-up" OR startup)) OR (green PRE/0 (innovation OR "tech* development" OR "industr* development" OR "tech* innovation" OR growth OR diversification OR entrepreneur* OR "start-up" OR startup))) AND (geograph* OR (spatial PRE/0 (scale OR dimension OR context)) OR (local PRE/0 (scale OR context OR development OR knowledge OR network)) OR (regional PRE/0 (scale OR level OR development OR econom* OR diversification OR branching OR analys*)) OR ((transnational OR international) PRE/0 (linkages OR level)))) AND (LIMIT-TO (SRCTYPE , "j"))	TS=(("eco-innovation*" OR "environmental innovation*" OR "sustainab* innovation*" OR ((clean-tech OR cleantech) NEAR/0 (innovation* OR industr* OR sector* OR "start-up*" OR startup*)) OR (green NEAR/0 (innovation* OR "tech* development" OR "industr* development" OR "tech* innovation*" OR growth OR diversification OR entrepreneur* OR "start-up*" OR startup*))) AND (geograph* OR (spatial NEAR/0 (scale* OR dimension* OR context*)) OR (local NEAR/0 (scale* OR context* OR development OR knowledge OR network*)) OR (regional NEAR/0 (scale* OR level* OR development OR econom* OR diversification OR branching OR analys*)) OR ((transnational OR international) NEAR/0 (linkages OR level)))) and Articles (Document Types)
Geography of sustainability transitions	TITLE-ABS-KEY (("sustainab* transition" OR "transition studies" OR "*technical transition" OR "socio-technical change" OR "multi-level perspective" OR "technological innovation system" OR "strategic niche management" OR "transition management" OR ("global innovation system" W/255 transition)) AND (geograph* OR (spatial PRE/0 (scale OR dimension OR context)) OR (regional PRE/0 (scale OR development OR innovation OR governance OR level)) OR (local PRE/0 (scale OR context OR development)) OR ((transnational OR international) PRE/0 (linkages OR level)))) AND (LIMIT-TO (SRCTYPE , "j"))	TS=(("sustainab* transition*" OR "transition studies" OR "*technical transition*" OR "socio-technical change" OR "multi-level perspective" OR "technological innovation system" OR "strategic niche management" OR "transition management" OR ("global innovation system" NEAR/255 transition*)) AND (geograph* OR (spatial NEAR/0 (scale* OR dimension* OR context*)) OR (regional NEAR/0 (scale* OR development OR innovation* OR governance OR level*)) OR (local NEAR/0 (scale* OR context* OR development)) OR ((transnational OR international) NEAR/0 (linkages OR level*)))) and Articles (Document Types)

Table A 2: Details of the publications included in the review

Related to both research streams				
No.	**Authors**	**Year**	**Title**	**Journal**
1.	Binz C., Tang T., Huenteler J.	2017	Spatial lifecycles of cleantech industries – The global development history of solar photovoltaics	Energy Policy
2.	Binz, C., Truffer, B., Coenen, L.	2016	Path Creation as a Process of Resource Alignment and Anchoring: Industry Formation for On-Site Water Recycling in Beijing	Economic Geography
3.	Boschma R., Coenen L., Frenken K., Truffer B.	2017	Towards a theory of regional diversification: combining insights from Evolutionary Economic Geography and Transition Studies	Regional Studies
4.	Calignano G., Fitjar R.D., Hjertvikrem N.	2019	Innovation networks and green restructuring: Which path development can EU Framework Programmes stimulate in Norway?	Norsk Geografisk Tidsskrift
5.	Capasso M., Hansen T., Heiberg J., Klitkou A., Steen M.	2019	Green growth – A synthesis of scientific findings	Technological Forecasting and Social Change
6.	Carvalho L., Mingardo G., van Haaren J.	2012	Green Urban Transport Policies and Cleantech Innovations: Evidence from Curitiba, Göteborg and Hamburg	European Planning Studies
7.	Coenen L.	2015	Engaging with changing spatial realities in TIS research	Environmental Innovation and Societal Transitions
8.	Cooke P.	2010	Socio-technical Transitions and Varieties of Capitalism: Green Regional Innovation and Distinctive Market Niches	Journal of the Knowledge Economy
9.	Cooke P.	2011	Transition regions: Regional-national eco-innovation systems and strategies	Progress in Planning
10.	Frank A.G., Gerstlberger W., Paslauski C.A., Lerman L.V., Ayala N.F.	2018	The contribution of innovation policy criteria to the development of local renewable energy systems	Energy Policy
11.	Gibbs D., O'Neill K.	2014	The green economy, sustainability transitions and transition regions: A case study of boston	Geografiska Annaler, Series B: Human Geography
12.	Gosens J., Lu Y., Coenen L.	2015	The role of transnational dimensions in emerging economy 'Technological Innovation Systems' for clean-tech	Journal of Cleaner Production
13.	Grillitsch M., Hansen T.	2019	Green industry development in different types of regions	European Planning Studies
14.	Longhurst N.	2015	Towards an 'alternative' geography of innovation: Alternative milieu, socio-cognitive protection and sustainability experimentation	Environmental Innovation and Societal Transitions
15.	Losacker S., Liefner I.	2020	Regional lead markets for environmental innovation	Environmental Innovation and Societal Transitions
16.	Lukkarinen J., Berg A., Salo M., Tainio P., Alhola K., Antikainen R.	2018	An intermediary approach to technological innovation systems (TIS)—The case of the cleantech sector in Finland	Environmental Innovation and Societal Transitions

17.	Nilsson M., Hillman K., Magnusson T.	2012	How do we govern sustainable innovations? Mapping patterns of governance for biofuels and hybrid-electric vehicle technologies	Environmental Innovation and Societal Transitions
18.	Quitzow R., Walz R., Köhler J., Rennings K.	2014	The concept of "lead markets" revisited: Contribution to environmental innovation theory	Environmental Innovation and Societal Transitions
19.	Raman S., Mohr A.	2014	Biofuels and the role of space in sustainable innovation journeys	Journal of Cleaner Production
20.	Santoalha A., Boschma R.	2021	Diversifying in green technologies in European regions: does political support matter?	Regional Studies
21.	Steen M., Faller F., Fyhn Ullern E.	2019	Fostering renewable energy with smart specialisation? Insights into European innovation policy	Norsk Geografisk Tidsskrift
22.	Strambach S.	2017	Combining Knowledge Bases in Transnational Sustainability Innovation: Microdynamics and Institutional Change	Economic Geography
23.	Toedtling F., Trippl, M., Frangenheim A.	2020	Policy options for green regional development: Adopting a production and application perspective	Science and Public Policy
24.	Trippl M., Baumgartinger-Seiringer S., Frangenheim A., Isaksen A., Rypestøl J.O.	2020	Unravelling green regional industrial path development: Regional preconditions, asset modification and agency	Geoforum
25.	Truffer B., Coenen L.	2012	Environmental Innovation and Sustainability Transitions in Regional Studies	Regional Studies
26.	Truffer B., Murphy J.T., Raven R.	2015	The geography of sustainability transitions: Contours of an emerging theme	Environmental Innovation and Societal Transitions

Geography of eco-innovations

No.	Author/s	Year	Title	Journal
1.	Aarstad J., Jakobsen S.-E.	2020	Norwegian firms' green and new industry strategies: A dual challenge	Sustainability
2.	Ai H., Deng Z., Yang X.	2015	The effect estimation and channel testing of the technological progress on China's regional environmental performance	Ecological Indicators
3.	Aldieri L., Ioppolo G., Vinci C.P., Yigitcanlar T.	2019	Waste recycling patents and environmental innovations: An economic analysis of policy instruments in the USA, Japan and Europe	Waste Management
4.	Aldieri L., Kotsemir M., Vinci C.P.	2019	The impact of environmental innovations on job-creation process: an empirical investigation for Russian regions	Environmental Economics and Policy Studies
5.	Aldieri L., Vinci C.P.	2019	Firm size and sustainable innovation: A theoretical and empirical analysis	Sustainability
6.	Antonioli D., Borghesi S., Mazzanti M.	2016	Are regional systems greening the economy? Local spillovers, green innovations and firms’ economic performances	Economics of Innovation and New Technology
7.	Ardito L., Messeni Petruzzelli A., Pascucci F., Peruffo E.	2018	Inter-firm R&D collaborations and green innovation value: The role of family firms' involvement and the moderating effects of proximity dimensions	Business Strategy and the Environment
8.	Arranz N., F. Arroyabe C., Fernandez de Arroyabe J.C.	2019	The effect of regional factors in the development of eco-innovations in the firm	Business Strategy and the Environment
9.	Barbieri N., Perruchas F., Consoli D.	2020	Specialization, Diversification, and Environmental Technology Life Cycle	Economic Geography

10.	Benedetti, R; Palma, D, Postiglione, P	2020	Modeling the Impact of Technological Innovation on Environmental Efficiency: A Spatial Panel Data Approach	Geographical Analysis
11.	Bermúdez-Edo M., Hurtado-Torres N.E., Ortiz-de-Mandojana N.	2017	The Influence of International Scope on the Relationship Between Patented Environmental Innovations and Firm Performance	Business and Society
12.	Cainelli G., D'Amato A., Mazzanti M.	2015	Adoption of waste-reducing technology in manufacturing: Regional factors and policy issues	Resource and Energy Economics
13.	Cainelli G., Mazzanti M., Montresor S.	2012	Environmental Innovations, Local Networks and Internationalization	Industry and Innovation
14.	Cainelli G., Mazzanti M., Zoboli R.	2011	Environmental innovations, complementarity and local/global cooperation: Evidence from North-East Italian industry	International Journal of Technology, Policy and Management
15.	Caprotti F.	2012	The cultural economy of cleantech: Environmental discourse and the emergence of a new technology sector	Transactions of the Institute of British Geographers
16.	Chapple K., Kroll C., William Lester T., Montero S.	2011	Innovation in the green economy: An extension of the regional innovation system model?	Economic Development Quarterly
17.	Chen J., Cheng J., Dai S.	2017	Regional eco-innovation in China: An analysis of eco-innovation levels and influencing factors	Journal of Cleaner Production
18.	Chiarvesio M., De Marchi V., Maria E.D.	2015	Environmental Innovations and Internationalization: Theory and Practices	Business Strategy and the Environment
19.	Colombelli A., Quatraro F.	2019	Green start-ups and local knowledge spillovers from clean and dirty technologies	Small Business Economics
20.	Cooke P.	2010	Regional innovation systems: Development opportunities from the 'green turn'	Technology Analysis and Strategic Management
21.	Cooke P.	2012	Transversality and Transition: Green Innovation and New Regional Path Creation	European Planning Studies
22.	Cooke P.	2015	Green governance and green clusters: Regional & national policies for the climate change challenge of Central & Eastern Europe	Journal of Open Innovation: Technology, Market, and Complexity
23.	Corradini C.	2019	Location determinants of green technological entry: evidence from European regions	Small Business Economics
24.	Corsatea, TD	2016	Localised knowledge, local policies and regional innovation activity for renewable energy technologies: Evidence from Italy	Papers in Regional Science
25.	Costantini V., Mazzanti M., Montini A.	2013	Environmental performance, innovation and spillovers. Evidence from a regional NAMEA	Ecological Economics
26.	da Silva Rabêlo O., de Azevedo Melo A.S.S.	2019	Drivers of multidimensional eco-innovation: empirical evidence from the Brazilian industry	Environmental Technology
27.	D'Agostino L.M., Moreno R.	2019	Green regions and local firms' innovation	Papers in Regional Science
28.	Davies, AR, Mullin, SJ	2011	Greening the economy: interrogating sustainability innovations beyond the mainstream	Journal of Economic Geography
29.	Dawley S.	2014	Creating New Paths? Offshore Wind, Policy Activism, and Peripheral Region Development	Economic Geography
30.	De Giorgi C., Dal Palù D., Allione C.	2015	Development and results of a cross border network project, aimed at the engineering of eco-compatible products	Journal of Cleaner Production

31.	DiVito L., Ingen-Housz Z.	2019	From individual sustainability orientations to collective sustainability innovation and sustainable entrepreneurial ecosystems	Small Business Economics
32.	Dong Z., He Y., Wang H., Wang L.	2020	Is there a ripple effect in environmental regulation in China? – Evidence from the local-neighborhood green technology innovation perspective	Ecological Indicators
33.	Du J.-L., Liu Y., Diao W.-X.	2019	Assessing regional differences in green innovation efficiency of industrial enterprises in China	International Journal of Environmental Research and Public Health
34.	Fabrizio, KR, Poczter, S, Zelner, BA	2017	Does innovation policy attract international competition? Evidence from energy storage	Research Policy
35.	Ferreira, JJM, Fernandes, CI, Ferreira, FAF	2020	Technology transfer, climate change mitigation, and environmental patent impact on sustainability and economic growth: A comparison of European countries	Technological Forecast and Social Change
36.	Florida R., Atlas M., Cline M.	2001	What makes companies green? Organizational and geographical factors in the adoption of environmental practices	Economic Geography
37.	Fu Y., Supriyadi A., Wang T., Wang L., Cirella G.T.	2020	Effects of regional innovation capability on the green technology efficiency of china's manufacturing industry: Evidence from listed companies	Energies
38.	Fusillo, F, Quatraro, F, Usai, S	2020	Going green: the dynamics of green technological alliances	Economics of Innovation and New Technology
39.	Galliano D., Gonçalves A., Triboulet P.	2019	The peripheral systems of eco-innovation: Evidence from eco-innovative agro-food projects in a French rural area	Journal of Rural Studies
40.	Georgeson L., Caprotti F., Bailey I.	2014	It's all a question of business': Investment identities, networks and decision-making in the cleantech economy	Geografiska Annaler, Series B: Human Geography
41.	Ghisetti C., Quatraro F.	2013	Beyond inducement in climate change: Does environmental performance spur environmental technologies? A regional analysis of cross-sectoral differences	Ecological Economics
42.	Ghisetti C., Quatraro F.	2017	Green Technologies and Environmental Productivity: A Cross-sectoral Analysis of Direct and Indirect Effects in Italian Regions	Ecological Economics
43.	Giudici G., Guerini M., Rossi-Lamastra C.	2019	The creation of cleantech startups at the local level: the role of knowledge availability and environmental awareness	Small Business Economics
44.	Grafstrom, J	2018	International knowledge spillovers in the wind power industry: evidence from the European Union	Economics of Innovation and New Technology
45.	Guo Y., Xia X., Zhang S., Zhang D.	2018	Environmental regulation, government R & D funding and green technology innovation: Evidence from China provincial data	Sustainability
46.	Hansen T.	2015	Substitution or Overlap? The Relations between Geographical and Non-spatial Proximity Dimensions in Collaborative Innovation Projects	Regional Studies
47.	Hansen T.	2014	Juggling with Proximity and Distance: Collaborative Innovation Projects in the Danish Cleantech Industry	Economic Geography
48.	Hess D.J., Sudibjo M.N.	2018	Supporting regional cleantech sectors in North America	Sustainability: Science, Practice, and Policy
49.	Horbach J.	2014	Do eco-innovations need specific regional characteristics? An econometric analysis for Germany	Review of Regional Research
50.	Horbach J., Rammer C.	2018	Energy transition in Germany and regional spill-overs: The diffusion of renewable energy in firms	Energy Policy
51.	Hu C., Mao J., Tian M., Wei Y., Guo L., Wang Z.	2021	Distance matters: Investigating how geographic proximity to ENGOs triggers green innovation of heavy-polluting firms in China	Journal of Environmental Management

52.	Krupoderova A., Portnov B.A.	2020	Eco-innovations and economic performance of regions: a systematic literature survey	Regional Studies, Regional Science
53.	Lansu A., Boon J., Sloep P.B., Van Dam-Mieras R.	2013	Changing professional demands in sustainable regional development: A curriculum design process to meet transboundary competence	Journal of Cleaner Production
54.	Li C., Wan J., Xu Z., Lin T.	2021	Impacts of green innovation, institutional constraints and their interactions on high-quality economic development across china	Sustainability
55.	Liu Y., Shao X., Tang M., Lan H.	2021	Spatio-temporal evolution of green innovation network and its multidimensional proximity analysis: Empirical evidence from China	Journal of Cleaner Production
56.	Liu Y., Zhu J., Li E.Y., Meng Z., Song Y.	2020	Environmental regulation, green technological innovation, and eco-efficiency: The case of Yangtze river economic belt in China	Technological Forecasting and Social Change
57.	Losacker S.	2020	The geography of green technology licensing in China	Regional Studies, Regional Science
58.	MacKinnon D., et al.	2019	Path creation, global production networks and regional development: A comparative international analysis of the offshore wind sector	Progress in Planning
59.	Mazzanti M.	2018	Eco-innovation and sustainability: dynamic trends, geography and policies	Journal of Environmental Planning and Management
60.	Montresor S., Quatraro F.	2020	Green technologies and Smart Specialisation Strategies: a European patent-based analysis of the intertwining of technological relatedness and key enabling technologies	Regional Studies
61.	Orsatti, G, Perruchas, F, Consoli, D, Quatraro, F	2020	Public Procurement, Local Labor Markets and Green Technological Change. Evidence from US Commuting Zones	Environmental and Resource Economics
62.	Panapanaan V., Uotila T., Jalkala A.	2014	Creation and Alignment of the Eco-innovation Strategy Model to Regional Innovation Strategy: A Case from Lahti (Päijät-Häme Region), Finland	European Planning Studies
63.	Park J.-I., Lee S.	2017	Examining the spatial patterns of green industries and the role of government policies in South Korea: Application of a panel regression model (2006–2012)	Renewable and Sustainable Energy Reviews
64.	Park, JI, Choi, T	2020	Related variety, unrelated variety, and R&D investment in the environmental industry	Asian Journal of Technology Innovation
65.	Peng, X	2020	Strategic interaction of environmental regulation and green productivity growth in China: Green innovation or pollution refuge?	Science of the Total Environment
66.	Perkins R.	2010	The internationalisation of managerial environmentalism: Globalisation, diffusion and territorialisation	Geography Compass
67.	Perruchas F., Consoli D., Barbieri N.	2020	Specialisation, diversification and the ladder of green technology development	Research Policy
68.	Potts T.	2010	The natural advantage of regions: linking sustainability, innovation, and regional development in Australia	Journal of Cleaner Production
69.	Quatraro, F, Scandura, A	2019	Academic Inventors and the Antecedents of Green Technologies. A Regional Analysis of Italian Patent Data	Ecological Economics
70.	Ratten V.	2018	Eco-innovation and competitiveness in the Barossa Valley wine region	Competitiveness Review
71.	Rinkinen S., Oikarinen T., Melkas H.	2016	Social enterprises in regional innovation systems: a review of Finnish regional strategies	European Planning Studies
72.	Schreurs M.	2017	Multi-level Climate Governance in China	Environmental Policy and Governance
73.	Smol M., Kulczycka J., Avdiushchenko A.	2017	Circular economy indicators in relation to eco-innovation in European regions	Clean Technologies and Environmental Policy

74.	Sotarauta M., Suvinen N.	2019	Place leadership and the challenge of transformation: policy platforms and innovation ecosystems in promotion of green growth	European Planning Studies
75.	Sotarauta M., Suvinen N., Jolly S., Hansen T.	2021	The many roles of change agency in the game of green path development in the North	European Urban and Regional Studies
76.	Sunny S.A., Shu C.	2019	Investments, incentives, and innovation: geographical clustering dynamics as drivers of sustainable entrepreneurship	Small Business Economics
77.	Ying L., Li M., Yang J.	2021	Agglomeration and driving factors of regional innovation space based on intelligent manufacturing and green economy	Environmental Technology and Innovation
78.	Yu N.	2017	Innovation of renewable energy generation technologies at a regional level in China: a study based on patent data analysis	International Economics and Economic Policy
79.	Zhou X., Yu Y., Yang F., Shi Q.	2021	Spatial-temporal heterogeneity of green innovation in China	Journal of Cleaner Production

Geography of sustainability transitions

No.	Authors	Year	Title	Journal
1.	Andersson J., Hellsmark H., Sandén B.A.	2018	Shaping factors in the emergence of technological innovations: The case of tidal kite technology	Technological Forecasting and Social Change
2.	Audouin S., Gazull L., Gautier D.	2018	Territory matters: Exploring the functioning of an innovation system through the filter of local territorial practices - the example of the adoption of cashew trees in Burkina Faso	Journal of Rural Studies
3.	Bai X., Wieczorek A.J., Kaneko S., Lisson S., Contreras A.	2009	Enabling sustainability transitions in Asia: The importance of vertical and horizontal linkages	Technological Forecasting and Social Change
4.	Bakker S., Leguijt P., Van Lente H.	2015	Niche accumulation and standardization - The case of electric vehicle recharging plugs	Journal of Cleaner Production
5.	Barnes J.	2019	The local embedding of low carbon technologies and the agency of user-side intermediaries	Journal of Cleaner Production
6.	Bauer F., Fuenfschilling L.	2019	Local initiatives and global regimes – Multi-scalar transition dynamics in the chemical industry	Journal of Cleaner Production
7.	Belmin R., Casabianca F., Meynard J.-M.	2018	Contribution of transition theory to the study of geographical indications	Environmental Innovation and Societal Transitions
8.	Bento N., Fontes M.	2015	Spatial diffusion and the formation of a technological innovation system in the receiving country: The case of wind energy in Portugal	Environmental Innovation and Societal Transitions
9.	Bergek A., Hekkert M., Jacobsson S., Markard J., Sandén B., Truffer B.	2015	Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics	Environmental Innovation and Societal Transitions
10.	Bichai F., Kajenthira Grindle A., Murthy S.L.	2018	Addressing barriers in the water-recycling innovation system to reach water security in arid countries	Journal of Cleaner Production
11.	Binz C., Coenen L., Murphy J.T., Truffer B.	2020	Geographies of transition—From topical concerns to theoretical engagement: A commentary on the transitions research agenda	Environmental Innovation and Societal Transitions
12.	Binz C., Truffer B.	2011	Technological innovation systems in multi-scalar space: Analyzing an emerging water recycling industry with social network analysis	Geographica Helvetica
13.	Binz C., Truffer B.	2017	Global Innovation Systems “a conceptual framework for innovation dynamics in transnational contexts	Research Policy

14.	Binz C., Truffer B., Coenen L.	2014	Why space matters in technological innovation systems - Mapping global knowledge dynamics of membrane bioreactor technology	Research Policy
15.	Binz C., Truffer B., Li L., Shi Y., Lu Y.	2012	Conceptualizing leapfrogging with spatially coupled innovation systems: The case of onsite wastewater treatment in China	Technological Forecasting and Social Change
16.	Binz, C, Anadon, LD	2018	Unrelated diversification in latecomer contexts: Emergence of the Chinese solar photovoltaics industry	Environmental Innovation and Societal Transitions
17.	Blum N.U., Bening C.R., Schmidt T.S.	2015	An analysis of remote electric mini-grids in Laos using the Technological Innovation Systems approach	Technological Forecasting and Social Change
18.	Boamah F.	2020	Emerging Low-Carbon Energy Landscapes and Energy Innovation Dilemmas in the Kenyan Periphery	Annals of the American Association of Geographers
19.	Bogedain A., Hamm R.	2020	Strengthening local economy – an example of higher education institutions' engagement in "co-creation for sustainability"	Region
20.	Bohnsack R.	2018	Local niches and firm responses in sustainability transitions: The case of low-emission vehicles in China	Technovation
21.	Bridge G., Bouzarovski S., Bradshaw M., Eyre N.	2013	Geographies of energy transition: Space, place and the low-carbon economy	Energy Policy
22.	Brunet C., Savadogo O., Baptiste P., Bouchard M.A., Cholez C., et. al	2021	The three paradoxes of the energy transition - Assessing sustainability of large-scale solar photovoltaic through multi-level and multi-scalar perspective in Rwanda	Journal of Cleaner Production
23.	Burnham, M, Eaton, W, Selfa, T, Hinrichs, C, Feldpausch-Parker, A	2017	The politics of imaginaries and bioenergy sub-niches in the emerging Northeast US bioenergy economy	Geoforum
24.	Calvert K.E., Kedron P., Baka J., Birch K.	2017	Geographical perspectives on sociotechnical transitions and emerging bio-economies: introduction to a special issue	Technology Analysis and Strategic Management
25.	Caprotti F.	2017	Protecting innovative niches in the green economy: investigating the rise and fall of Solyndra, 2005–2011	GeoJournal
26.	Chandrashekeran S.	2016	Multidimensionality and the multilevel perspective: Territory, scale, and networks in a failed demand-side energy transition in Australia	Environment and Planning A
27.	Chlebna, C, Mattes, J	2020	The fragility of regional energy transitions	Environmental Innovation and Societal Transitions
28.	Coenen L., Benneworth P., Truffer B.	2012	Toward a spatial perspective on sustainability transitions	Research Policy
29.	Coenen L., Hansen T., Rekers J.V.	2015	Innovation Policy for Grand Challenges. An Economic Geography Perspective	Geography Compass
30.	Coenen L., Moodysson J., Martin H.	2015	Path Renewal in Old Industrial Regions: Possibilities and Limitations for Regional Innovation Policy	Regional Studies
31.	Coenen L., Raven R., Verbong G.	2010	Local niche experimentation in energy transitions: A theoretical and empirical exploration of proximity advantages and disadvantages	Technology in Society
32.	Coenen L., Truffer B.	2012	Places and Spaces of Sustainability Transitions: Geographical Contributions to an Emerging Research and Policy Field	European Planning Studies
33.	Cowell, R, Ellis, G, Sherry-Brennan, F, Strachan, PA, Toke, D	2017	Energy transitions, sub-national government and regime flexibility: How has devolution in the United Kingdom affected renewable energy development?	Energy Research & Social Science

34.	D'Adamo I., Falcone P.M., Imbert E., Morone P.	2020	Exploring regional transitions to the bioeconomy using a socio-economic indicator: the case of Italy	Economia Politica
35.	Damman S., Steen M.	2021	A socio-technical perspective on the scope for ports to enable energy transition	Transportation Research Part D: Transport and Environment
36.	De Boer, J, Zuidema, C, Gugerell, K	2018	New interaction paths in the energy landscape: the role of local energy initiatives	Landscape Research
37.	de Haan F., Moors E.H.M., Dondorp A.M., Boon W.P.C.	2021	Market Formation in a Global Health Transition	Environmental Innovation and Societal Transitions
38.	De Laurentis C.	2015	Innovation and Policy for Bioenergy in the UK: A Co-Evolutionary Perspective	Regional Studies
39.	De Oliveira L.G.S., Negro S.O.	2019	Contextual structures and interaction dynamics in the Brazilian Biogas Innovation System	Renewable and Sustainable Energy Reviews
40.	Dewald U., Fromhold-Eisebith M.	2015	Trajectories of sustainability transitions in scale-transcending innovation systems: The case of photovoltaics	Environmental Innovation and Societal Transitions
41.	Dewald U., Truffer B.	2012	The Local Sources of Market Formation: Explaining Regional Growth Differentials in German Photovoltaic Markets	European Planning Studies
42.	Doyon A., Coffey B., Moloney S., De Haan F., Bosomworth K.	2017	Exploring the contribution of transitions management to inform regional futures	Australasian Journal of Regional Studies
43.	El Bilali H.	2019	Research on agro-food sustainability transitions: A systematic review of research themes and an analysis of research gaps	Journal of Cleaner Production
44.	Essletzbichler J.	2012	Renewable Energy Technology and Path Creation: A Multi-scalar Approach to Energy Transition in the UK	European Planning Studies
45.	Faller, F	2016	A practice approach to study the spatial dimensions of the energy transition	Environmental Innovation and Societal Transitions
46.	Fontaine A.	2020	Debating the sustainability of solar energy: Examining resource construction processes for local photovoltaic projects in France	Energy Research and Social Science
47.	Fontes M., Sousa C., Ferreira J.	2016	The spatial dynamics of niche trajectory: The case of wave energy	Environmental Innovation and Societal Transitions
48.	Friis, C, Becker, S	2020	Thinking through connections in food and energy transitions Introduction	Geografiska Annaler, Series B: Human Geography
49.	Fuenfschilling L., Binz C.	2018	Global socio-technical regimes	Research Policy
50.	Gebauer H., Binz C.	2019	Regional benefits of servitization processes: evidence from the wind-to-energy industry	Regional Studies
51.	Gibbs D., O'Neill K.	2017	Future green economies and regional development: a research agenda	Regional Studies
52.	Gustafsson S., Mignon I.	2020	Municipalities as intermediaries for the design and local implementation of climate visions	European Planning Studies
53.	Haarstad H., Rusten G.	2016	The challenges of greening energy: policy/industry dissonance at the Mongstad refinery, Norway	Environment and Planning C: Government and Policy
54.	Hansen T., Coenen L.	2015	The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field	Environmental Innovation and Societal Transitions
55.	Hansen U.E., Nygaard I.	2013	Transnational linkages and sustainable transitions in emerging countries: Exploring the role of donor interventions in niche development	Environmental Innovation and Societal Transitions

56.	Hansen U.E., Nygaard I., Romijn H., Wieczorek A., Kamp L.M., Klerkx L.	2018	Sustainability transitions in developing countries: Stocktaking, new contributions and a research agenda	Environmental Science and Policy
57.	Hawkey D.J.C.	2012	District heating in the UK: A Technological Innovation Systems analysis	Environmental Innovation and Societal Transitions
58.	Häyrynen S., Hämeenaho P.	2020	Green clashes: cultural dynamics of scales in sustainability transitions in European peripheries	Palgrave Communications
59.	Hermans F.	2018	The potential contribution of transition theory to the analysis of bioclusters and their role in the transition to a bioeconomy	Biofuels, Bioproducts and Biorefining
60.	Hermans F., Roep D., Klerkx L.	2016	Scale dynamics of grassroots innovations through parallel pathways of transformative change	Ecological Economics
61.	Hess D.J., Mai Q.D., Skaggs R., Sudibjo M.	2018	Local matters: Political opportunities, spatial scale, and support for green jobs policies	Environmental Innovation and Societal Transitions
62.	Hojckova K., Ahlborg H., Morrison G.M., Sandén B.	2020	Entrepreneurial use of context for technological system creation and expansion: The case of blockchain-based peer-to-peer electricity trading	Research Policy
63.	Hoppe T., Miedema M.	2020	A governance approach to regional energy transition: Meaning, conceptualization and practice	Sustainability
64.	Isaksson K., Hagbert P.	2020	Institutional capacity to integrate 'radical' perspectives on sustainability in small municipalities: experiences from Sweden	Environmental Innovation and Societal Transitions
65.	Jedelhauser M., Binder C.R.	2018	The spatial impact of socio-technical transitions – The case of phosphorus recycling as a pilot of the circular economy	Journal of Cleaner Production
66.	Jiusto S., McCauley S.	2010	Assessing sustainability transition in the US electrical power system	Sustainability
67.	Kirshner J., Baker L., Smith A., Bulkeley H.	2019	A regime in the making? Examining the geographies of solar PV electricity in Southern Africa	Geoforum
68.	Klitkou A., Coenen L.	2013	The Emergence of the Norwegian Solar Photovoltaic Industry in a Regional Perspective	European Planning Studies
69.	Köhler J., Geels F.W., Kern F., Markard J., Onsongo E., et al.	2019	An agenda for sustainability transitions research: State of the art and future directions	Environmental Innovation and Societal Transitions
70.	Lawhon M., Murphy J.T.	2012	Socio-technical regimes and sustainability transitions: Insights from political ecology	Progress in Human Geography
71.	Levin-Keitel M., Mölders T., Othengrafen F., Ibendorf J.	2018	Sustainability transitions and the spatial interface: Developing conceptual perspectives	Sustainability
72.	Loorbach D., Wittmayer J., Avelino F., von Wirth T., Frantzeskaki N.	2020	Transformative innovation and translocal diffusion	Environmental Innovation and Societal Transitions
73.	Lovio R., Kivimaa P.	2012	Comparing Alternative Path Creation Frameworks in the Context of Emerging Biofuel Fields in the Netherlands, Sweden and Finland	European Planning Studies
74.	Lutz L.M., Fischer L.-B., Newig J., Lang D.J.	2017	Driving factors for the regional implementation of renewable energy - A multiple case study on the German energy transition	Energy Policy
75.	MacKinnon D., Dawley S., Pike A., Cumbers A.	2019	Rethinking Path Creation: A Geographical Political Economy Approach	Economic Geography
76.	Magro E., Wilson J.R.	2019	Policy-mix evaluation: Governance challenges from new place-based innovation policies	Research Policy

77.	Martin H.	2020	The scope of regional innovation policy to realize transformative change–a case study of the chemicals industry in western Sweden	European Planning Studies
78.	Martin H., Coenen L.	2015	Institutional Context and Cluster Emergence: The Biogas Industry in Southern Sweden	European Planning Studies
79.	Matschoss K., Repo P., Timonen P.	2019	Embedding European citizen visions in sustainability transition: Comparative analysis across 30 European countries	Futures
80.	Mattes J., Huber A., Koehrsen J.	2015	Energy transitions in small-scale regions - What we can learn from a regional innovation systems perspective	Energy Policy
81.	McCauley S.M., Stephens J.C.	2012	Green energy clusters and socio-technical transitions: Analysis of a sustainable energy cluster for regional economic development in Central Massachusetts, USA	Sustainability Science
82.	Meelen T., Frenken K., Hobrink S.	2019	Weak spots for car-sharing in The Netherlands? The geography of socio-technical regimes and the adoption of niche innovations	Energy Research and Social Science
83.	Meyer T.	2021	Relational territoriality and the spatial embeddedness of nuclear energy: A comparison of two nuclear power plants in Germany and France	Energy Research and Social Science
84.	Morton, C, Wilson, C, Anable, J	2018	The diffusion of domestic energy efficiency policies: A spatial perspective	Energy Policy
85.	Munro F.R.	2019	Renewable energy and transition-periphery dynamics in Scotland	Environmental Innovation and Societal Transitions
86.	Munro F.R.	2019	The geography of socio-technical transitions: Transition–periphery dynamics	Geographical Journal
87.	Mura M., Longo M., Toschi L., Zanni S., Visani F., Bianconcini S.	2021	The role of geographical scales in sustainability transitions: An empirical investigation of the European industrial context	Ecological Economics
88.	Murphy J., Smith A.	2013	Understanding Transition—Periphery Dynamics: Renewable Energy in the Highlands and Islands of Scotland	Environment and Planning A: Economy and Space
89.	Murphy J.T.	2015	Human geography and socio-technical transition studies: Promising intersections	Environmental Innovation and Societal Transitions
90.	Murphy J.T.	2013	Transforming small, medium, and microscale enterprises? Information-communication technologies (ICTs) and industrial change in Tanzania	Environment and Planning A
91.	Nilsson M., Nykvist B.	2016	Governing the electric vehicle transition – Near term interventions to support a green energy economy	Applied Energy
92.	Njøs R., Sjøtun S.G., Jakobsen S.-E., Fløysand A.	2020	Expanding Analyses of Path Creation: Interconnections between Territory and Technology	Economic Geography
93.	Normann H.E., Hanson J.	2018	The role of domestic markets in international technological innovation systems	Industry and Innovation
94.	Noseleit F.	2018	Renewable energy innovations and sustainability transition: How relevant are spatial spillovers?	Journal of Regional Science
95.	Nygaard, I, Bolwig, S	2018	The rise and fall of foreign private investment in the jatropha biofuel value chain in Ghana	Environmental Science and Policy
96.	Papachristos G.	2017	Diversity in technology competition: The link between platforms and sociotechnical transitions	Renewable and Sustainable Energy Reviews
97.	Pflitsch G., Radinger-Peer V.	2018	Developing boundary-spanning capacity for regional sustainability transitions-A comparative case study of the universities of Augsburg (Germany) and Linz (Austria)	Sustainability

98.	Power M., Newell P., Baker L., Bulkeley H., Kirshner J., Smith A.	2016	The political economy of energy transitions in Mozambique and South Africa: The role of the Rising Powers	Energy Research and Social Science
99.	Quitzow R.	2015	Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany	Environmental Innovation and Societal Transitions
100.	Radinger-Peer V., Pflitsch G.	2017	The role of higher education institutions in regional transition paths towards sustainability: The case of Linz (Austria)	Review of Regional Research
101.	Ramiller A., Schmidt P.	2018	Scale limits to sustainability: Transdisciplinary evidence from three Danish cases	Environmental Innovation and Societal Transitions
102.	Raven R., Schot J., Berkhout F.	2012	Space and scale in socio-Technical transitions	Environmental Innovation and Societal Transitions
103.	Rodrigo P., Muñoz P., Wright A.	2015	Transitions dynamics in context: Key factors and alternative paths in the sustainable development of nations	Journal of Cleaner Production
104.	Roesler T.	2019	Community resources for energy transition: Implementing bioenergy villages in Germany	Area
105.	Roesler T., Hassler M.	2019	Creating niches – The role of policy for the implementation of bioenergy village cooperatives in Germany	Energy Policy
106.	Rohe S., Chlebna C.	2021	A spatial perspective on the legitimacy of a technological innovation system: Regional differences in onshore wind energy	Energy Policy
107.	Rohe S.	2020	The regional facet of a global innovation system: Exploring the spatiality of resource formation in the value chain for onshore wind energy	Environmental Innovation and Societal Transitions
108.	Santos D., Lane R.	2017	A material lens on socio-technical transitions: The case of steel in Australian buildings	Geoforum
109.	Sawulski J., Gałczyński M., Zajdler R.	2019	Technological innovation system analysis in a follower country – The case of offshore wind in Poland	Environmental Innovation and Societal Transitions
110.	Schäpke N., Omann I., Wittmayer J.M., van Steenbergen F., Mock M.	2017	Linking transitions to sustainability: A study of the societal effects of transition management	Sustainability
111.	Schmidt T.S., Dabur S.	2014	Explaining the diffusion of biogas in India: A new functional approach considering national borders and technology transfer	Environmental Economics and Policy Studies
112.	Schmitt D., Muyoya C.	2020	Influence in technological innovation spaces: A network science approach to understand innovation for sustainability in the global south	Sustainability
113.	Schwanen T.	2018	Thinking complex interconnections: Transition, nexus and Geography	Transactions of the Institute of British Geographers
114.	Sengers F., Raven R.	2015	Toward a spatial perspective on niche development: The case of Bus Rapid Transit	Environmental Innovation and Societal Transitions
115.	Sjøtun S.G.	2020	The role of engineers in the greening of the South-Western Norwegian Maritime Industry: Practices, agency and social fields	Geoforum
116.	Sjøtun S.G., Njøs R.	2019	Green reorientation of clusters and the role of policy: 'the normative' and 'the neutral' route	European Planning Studies
117.	Skellern, K, Markey, R, Thornthwaite, L	2017	Identifying attributes of sustainable transitions for traditional regional manufacturing industry sectors - A conceptual framework	Journal of Cleaner Production
118.	Smith T.S.J.	2020	Policy, polycentrism, and practice: Governance imaginaries in sustainability transitions	Area

119.	Späth P., Rohracher H.	2010	'Energy regions': The transformative power of regional discourses on socio-technical futures	Research Policy
120.	Späth P., Rohracher H.	2012	Local Demonstrations for Global Transitions-Dynamics across Governance Levels Fostering Socio-Technical Regime Change Towards Sustainability	European Planning Studies
121.	Steen M.	2016	Reconsidering path creation in economic geography: aspects of agency, temporality and methods	European Planning Studies
122.	Strambach S., Pflitsch G.	2018	Micro-dynamics in regional transition paths to sustainability - Insights from the Augsburg region	Applied Geography
123.	Strambach S., Pflitsch G.	2020	Transition topology: Capturing institutional dynamics in regional development paths to sustainability	Research Policy
124.	Suitner, J, Ecker, M	2020	Making energy transition work: Bricolage in Austrian regions' path-creation	Environmental Innovation and Societal Transitions
125.	Tani A., Lopolito A., Morone P.	2021	Spatial perspectives on niche empowerment: an agent-based model	Regional Studies
126.	Van Boxstael A., Meijer L.L.J., Huijben J.C.C.M., Romme A.G.L.	2020	Intermediating the energy transition across spatial boundaries: Cases of Sweden and Spain	Environmental Innovation and Societal Transitions
127.	van den Berge M., Weterings A., Alkemade F.	2020	Do existing regional specialisations stimulate or hinder diversification into cleantech?	Environmental Innovation and Societal Transitions
128.	van den Heiligenberg H.A.R.M., Heimeriks G.J., Hekkert M.P., van Oort F.G.	2017	A habitat for sustainability experiments: Success factors for innovations in their local and regional contexts	Journal of Cleaner Production
129.	Veldhuizen C.	2020	Smart Specialisation as a transition management framework: Driving sustainability-focused regional innovation policy?	Research Policy
130.	Veldhuizen C.	2021	Conceptualising the foundations of sustainability focused innovation policy: From constructivism to holism	Technological Forecasting and Social Change
131.	Vermunt D.A., Negro S.O., Van Laerhoven F.S.J., Verweij P.A., Hekkert M.P.	2020	Sustainability transitions in the agri-food sector: How ecology affects transition dynamics	Environmental Innovation and Societal Transitions
132.	Wesseling J.H.	2016	Explaining variance in national electric vehicle policies	Environmental Innovation and Societal Transitions
133.	Wieczorek A.J.	2018	Sustainability transitions in developing countries: Major insights and their implications for research and policy	Environmental Science and Policy
134.	Wieczorek A.J., Hekkert M.P., Coenen L., Harmsen R.	2015	Broadening the national focus in technological innovation system analysis: The case of offshore wind	Environmental Innovation and Societal Transitions
135.	Wieczorek A.J., Raven R., Berkhout F.	2015	Transnational linkages in sustainability experiments: A typology and the case of solar photovoltaic energy in India	Environmental Innovation and Societal Transitions
136.	Wilkinson S., Davidson M., Morrison G.M.	2020	Historical transitions of Western Australia's electricity system, 1880-2016	Environmental Innovation and Societal Transitions

Appendix B

Table A 3: Overview of data sources and search strategies

	Incumbents: PATSTAT Database (EPO)	**Start-ups: Mannheim Enterprise Panel (MUP)**
Transport	*IPC and Technology Concordance Table* (Schmoch 2008) B60 Vehicles in General B61 Railways B62 Land vehicles for travelling otherwise than on rails B63 Ships or other waterborne vessels; related equipment B64 Aircraft; Aviation; Cosmonautics	*Industry sector codes (NACE Rev. 2)* 29 Manufacture of motor vehicles, trailers and semi-trailers 30 Manufacture of other transport equipment 49 Land transport and transport via pipelines 50 Water transport 51 Air transport
Green transport	*Corporate Patent Classification (CPC)* Y02T Climate Change Mitigation Technologies related to transportation Y02T 10/00 Road transport of goods or passengers Y02T 30/00 Transportation of goods or passengers via railways Y02T 50/00 Aeronautics or air transport Y02T 70/00 Maritime or waterways transport Y02T 90/00 Enabling technologies or technologies with a potential or indirect contribution to GHG emissions mitigation	*Keyword-based search strategy (search terms derived from several sources: CPC Y02T class;* Cojoianu et al. (2020)*; "StartGreen" - information and networking portal for the green start-up scene in Germany)* e.g.* sustainable mobility; mobility transition; climate-neutral / low-emission / emission-free transport; electromobility; electric / hybrid ship; fuel cell; micro mobility; charging infrastructure; e-fuel; light vehicle; bicycle trailer; e-bike; car sharing; ridesharing; last mile; fleet management; green logistics *translated into German.

Table A 4: Descriptive statistics and correlations of variables

	Variable	Description	Mean	SD	Min.	Max.	1	2	3	4	5	6	7	8
1	Population density	Population per km^2	329	502	42	4,055	1							
2	GDP per capita	Gross domestic product (GDP) per capita (in EUR)	32,676	8,220	17,935	66,429	0.35***	1						
3	High-skilled individuals	Share of employees with an academic degree	11.3	3.8	5.0	28.3	0.49***	0.56***	1					
4	Car industry site	Share of employees working in knowledge- or research-intensive industries	0.1	0		1	0.10***	0.37***	0.31***	1				
5	Large enterprises	Share of companies with more than 250 employees	0.3	0.1	0.1	0.6	0.32***	0.55***	0.35***	0.15***	1			
6	R&D-intensive industries	Location of a car manufacturer with more than 10,000 employees (1 if yes)	10.2	5.5	0.8	28.3	-0.11***	0.43***	-0.06**	0.25***	0.23***	1		
7	Public transport	Distance to the nearest public transport stop with at least 20 departures per day in 2020 (1 if below median value)	0.5		0	1	0.40***	0.32***	0.53***	0.24***	0.38***	0.10***	1	
8	Green votes	Share of votes for "the Greens" in the 2009, 2013, 2017 fed. elections	8.4	3.1	2.8	17.4	0.38***	0.49***	0.31***	0.19***	0.16***	0.25***	0.37***	1

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

Appendix C

Table A 5: 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 related research projects (e.g., Rammer et al. 2023).

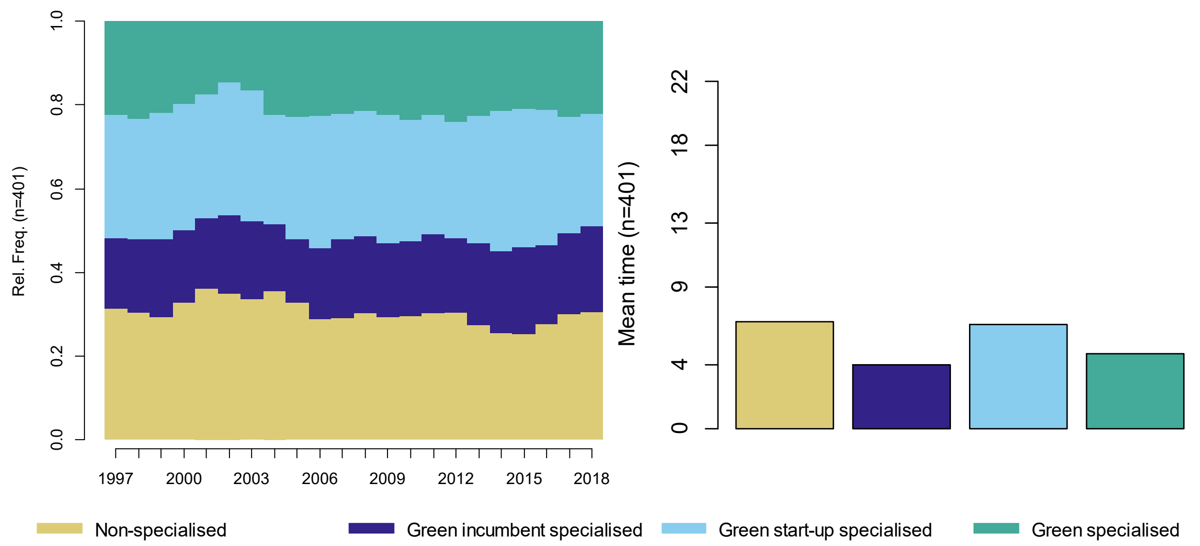

Figure A 1: Relative frequency and mean time of regional eco-innovation specialisation

Table A 6: 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-specialised 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, Newsham, and Rowe (2023)).

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

Characterising the different type of regions

Following the elaborations in Section 7.4.2, this appendix provides an in-depth discussion of trajectory-specific characteristics to further validate the spatio-temporal patterns of regional eco-innovation specialisations observed in this study. 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 into possible influencing factors that require further in-depth analyses.

Figure A 2 illustrates the mentioned 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 urbanisation rate, while outliers in non-specialised 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 an unemployment rate of about three percent which is by far the lowest, suggesting that a prosperous labour 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 specialisation 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. At first glance, much more remarkable is that green regions appear to generate the lowest monthly median income (about 3,000 EUR). However, many of the green regions are located in eastern Germany (see Figure 7 in the main article), which is still characterised by lower economic prosperity and average incomes. Greening regions are roughly equivalent to their related actor specialisation, with green start-up regions having a lower median income than green incumbent regions.

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 characterised 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 favourable 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 differences within the same types of regions are often greater than those between them. This partly strong variance makes it harder to explain spatio-temporal patterns and categorise accordingly, calling for extensive in-depth analyses in future research.

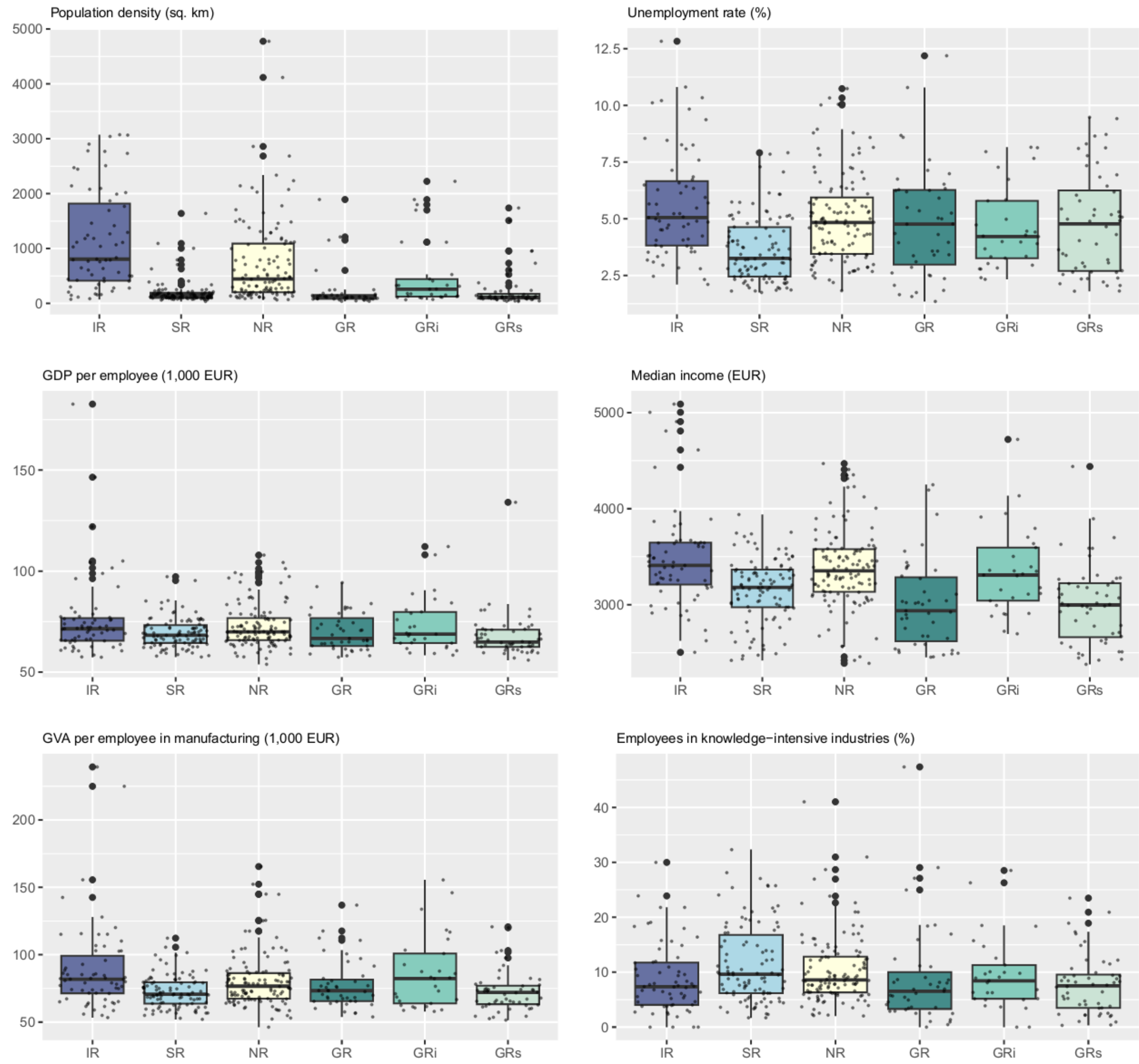

Figure A 2: Socio-economic characterisation of regional eco-innovation trajectories (data for 2019/2020; Federal Institute for Research on Building, Urban Affairs and Spatial Development, 2023)

Curriculum Vitae

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2016-2018	**Economic Geography, M. A.** at Leibniz University Hannover
2017-2018	**Semester Abroad** at Jagiellonian University Kraków
2012-2016	**Geography, B. Sc.** at University of Marburg

Secondary Education

2002-2011	**Higher Education Entrance Qualification** at Gymnasium Marienschule Lippstadt

List of Publications

Hansmeier, H. 2021. *Geography of eco-innovations vis-à-vis geography of sustainability transitions: Two sides of the same coin?* GEIST – Geography of Innovation and Sustainability Transitions (07).

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