



The geography of environmental innovation: a critical review and agenda for future research

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Abstract This article provides a critical literature review on the regional determinants of environmental innovation. The analysis of the relevant literature on supply-side factors, demand-side factors, and institutional factors reveals the importance of regional determinants in green technology development. Specifically, regional R&D collaborations, university-industry collaborations, and technological relatedness have positive effects on innovation activities in green domains. On the demand side, regional environmental awareness and demonstration effects play a pivotal role in the emergence and diffusion of environmental innovations. Environmental regulations also induce environmental innovation, however, there is only limited evidence at the regional level. Our literature review has informed the development of an agenda for future research, which suggests three avenues for further investigation. Firstly, we recommend abandoning the simple green vs. non-green dichotomy and conducting more technology-sensitive studies on the determinants of environmental innovation. Secondly, we call for a more sophisticated and critical engagement with regional institutions, with a focus on both formal and informal institutions. Lastly, we propose a demand-side turn in research on the regional determinants of environmental innovation in order to better understand their diffusion across space. Overall, our findings suggest that policymakers need to adopt a more nuanced and

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comprehensive approach to eco-innovation policy, one that considers the spatial and multi-level governance challenges and promotes inclusive regional development.

Keywords Environmental innovation · Geography of innovation · Sustainability transitions · Regional development · Green technology

1 Introduction

The emergence and diffusion of environmental innovations is of utmost importance to combat and mitigate negative environmental impacts brought about by human-environment interactions. Environmental innovations can contribute to solving global challenges at the regional level, with regions being key arenas for developing environmental innovation, for pioneering their application, and for promoting widespread use and diffusion.

In recent years, the analysis of environmentally related innovations has become an increasingly popular research topic in regional studies, which is evident, for example, from multiple dedicated sessions at the ‘Geography of Innovation’ conferences and growing numbers of research articles. Moreover, researchers from the broader fields of innovation studies or environmental economics are increasingly focusing on regional factors in their research as well (Antonioli et al. 2016; Cainelli et al. 2012; Horbach 2014; Horbach and Rammer 2018). Consequently, a large body of literature has emerged in recent years that, to put it concisely, addresses *the geography of environmental innovation*.

However, the literature on the geography of environmental innovation in regional studies is very heterogeneous, with different communities exploring different phenomena. Broadly speaking, we can distinguish three main (partly overlapping) strands of research. (1) The first strand focuses on green technological innovations and tries to understand which regional determinants matter for the development and diffusion of these technologies (e.g. Barbieri et al. 2020b; Galliano et al. 2022; Li et al. 2021; Losacker et al. 2023; Montresor and Quatraro 2020; Ocampo-Corrales et al. 2021; Santoalha and Boschma 2021). This field originates from the traditional literature on the geography of innovation at the intersection of economic geography and innovation studies, mainly using quantitative analyses of innovation data on the regional level. The field strongly builds on early work on the determinants of environmental innovation, which has long been blind to spatial aspects and regional contexts (Barbieri et al. 2016; Hojnik and Ruzzier 2016; Horbach 2008; Rennings 2000). We will focus on this strand of research in this paper. (2) A second and related research strand deals with the production of environmental innovations and their markets, studying green industries and green regional development (e.g. Bækkelund 2022; Gibbs and O’Neill 2017; Grillitsch and Hansen 2019; Trippl et al. 2020). This field predominantly draws on insights from the literature on evolutionary economic geography and new industrial path development. (3) A third community of researchers is working in the field of sustainability transitions and investigates which spatial factors contribute to the diffusion of environmental innovations, which might enable socio-technical change beyond the regional level (e.g. Binz et al. 2014,

Table 1 Main research strands on environmental innovation in regional studies (own compilation)

Field of research	(1) Regional determinants of environmental innovation and green technologies	(2) Green regional industrial path development	(3) Geography of sustainability transitions
Aim	Understanding (regional) determinants of green technology development and diffusion	Understanding how regions can establish green industrial paths	Understanding multi-scalar dynamics of socio-technical transitions
Conception and operationalization of geography	Regional factors for the development and diffusion of green technologies; (inter)regional spillovers; administrative borders of regions	Development of green industries in different types of regions; regional and extra-regional factors	Regional, national and global transformation processes; Local-global interdependencies; Multi-scalar and relational perspectives on space
Conception of innovation	Technological innovations	Green industries supplying technological, product or service innovations	Technological and non-technological innovation, including social innovation
Innovation phase	Focus on inventions and innovation development; Few studies on innovation adoption and diffusion	Focus on the production of green technologies, goods and services (i.e. green industries)	Focus on innovation diffusion and socio-technical regime change; Niche development
Methodology	Mainly quantitative analyses and econometric methods; cross-sectional and panel designs; quantitative innovation data (i.e. patents, firm data)	Mainly qualitative analyses and case-based studies; single case or multi case study designs; qualitative interview and document data	Mainly qualitative analyses and case-based studies; single case or multi case study designs; qualitative interview and document data
Intellectual origin	Literature on geography of innovation; Literature on determinants of environmental innovation	Literature on regional path development; Evolutionary economic geography	Science and technology studies; Literature at the intersection of human geography and transition studies

The classification into these three strands of research is not clear-cut, but rather a broad synthesis of the main research directions. Of course, research overlaps to some extent.

2020; Mörner and Binz 2021; Rohe and Chlebna 2021; Späth and Rohrer 2012; Strambach and Pflitsch 2018). We compare these different fields of research in more detail in Table 1.

As outlined above, the literature on environmental innovation in regional studies is fragmented across several research fields and, in consequence, the regional studies community lacks a critical overview of the importance of regions in the development and diffusion of environmental innovations. The scholarly fields mentioned above focus on different stages of the innovation process (e.g. invention, production, diffusion), employ different epistemological and methodological approaches, and have different understandings of why and how geography matters for environmental innovation. Scholars in regional studies might therefore struggle to assess the importance of regional (subnational) factors for environmental innovation.

While there are important review articles at the intersection of regional studies and environmental innovation (Coenen et al. 2012; Grillitsch and Hansen 2019; Truffer and Coenen 2012), we feel that they emphasize multi-scalar and exogenous

processes that affect regional innovation activities in green domains. In recognition of these important contributions, we argue that a review and agenda of explicitly endogenous or region-internal factors is still missing in the literature. A seminal contribution on regional factors has been put forward by Hansen and Coenen (2015). However, they address regional transition paths towards sustainability and the role of regions for the transition of socio-technical systems, which are long-term and complex *transformation processes* of sectors. This paper will focus on regional factors shaping the *innovation process* of green technologies that eventually enable deeper system changes. In other words, we are interested in understanding regions, not sectors (see also Boschma et al. 2017, p. 7). We therefore consider our paper complementary to the previously mentioned contributions. As such, this paper will focus on regional drivers of green technology development and diffusion (research strand 1 in Table 1). We will occasionally refer to important insights from the other two research streams throughout the paper.

Apart from that, we argue that previous research on regional drivers of environmental innovation has been unbalanced. Analyses of the regional conditions affecting the generation of environmental innovations tend to dominate, while the equally important aspects of scaling-up and diffusion have so far been under-researched. In order to fill these gaps, this article has two main objectives. Firstly, the article aims to review the current state of research on regional determinants of environmental innovation and green technologies, including both innovation emergence and diffusion. We thus seek to identify region-specific factors that can explain why some regions show better conditions for environmental innovation than others. Secondly, drawing on our critical review, the article aims to develop an agenda for further research on the geography of environmental innovation and green technology in regional studies.

The remainder of this article is structured as follows. In Section 2, we discuss the conceptual background and the characteristics of environmental innovation and how they are relevant from a regional perspective. Section 3 encompasses the literature review, summarizing regional supply-side and demand-side determinants as well as regional institutional and political determinants of environmental innovation that have been identified in previous research. In Section 4, we provide suggestions for future research. In this context, we point to important lessons from transition studies and path development literature such as accounting for technology-specific dynamics and regional informal institutions. We also indicate methodological advances that have so far been insufficiently exploited in regional research on green technologies. Lastly, we call for a demand-side turn in research on the geography of environmental innovation. Our concluding remarks as well as implications for policy are presented in Section 5.

2 Environmental innovation: what is it and why should we care about its geography?

An environmental innovation or (eco-innovation)¹ is a ‘[...] *new or improved product or practice of a unit that generates lower environmental impacts, compared to the unit’s previous products or practices, and that has been made available to potential users or brought into use by the unit*’ (Kemp et al. 2019, p. 35). This definition builds on earlier approaches (Arundel and Kemp 2009; Rennings 2000) and summarizes the core meaning in a relatively straightforward way: an environmental innovation is new and is introduced to the market (innovation part, see also OECD Oslo Manual), and it reduces environmental harm (environmental part). The environmental effect of eco-innovations can stem from lower resource use (e.g. energy efficiency), lower levels of pollution (e.g. filtering technologies) or any other form of reduced negative environmental impacts. Other definitions might further discern whether the beneficial effects on the environment are intended or not, they might distinguish between innovations according to the degree of environmental impact or they might explicitly include social or organizational innovations as well. That said, the use of the term environmental innovation in this article is largely limited to green technologies, goods and processes, and disregards other forms of innovation (e.g. business models). It is important to note that the review in this paper is therefore also limited to technological innovations. However, this does not imply that the regional level is less important for non-technological environmental innovations.

From a social science perspective, green technologies and environmental innovations feature some interesting peculiarities and they therefore differ from regular technologies and innovations. Arguably the most important peculiarity of environmental innovations is the so-called double-externality problem. That is to say, they generate positive spillovers in two phases: innovation development and innovation diffusion. The former is a general problem of innovations. Organizations that invest in R&D produce knowledge that can be used by other organizations which, however, do not bear any of the costs. This chronic problem of free-riding is prevented mainly through governmental R&D subsidies, first-mover advantages and an elaborate intellectual property rights system. However, environmental innovations also produce positive spillovers in the diffusion phase, as adopters contribute to reducing negative environmental impacts. While this has a non-excludable positive effect on other organizations and on society as a whole, adopters alone bear the costs. Accordingly, this double-externality problem might cause firms and other organizations to underinvest in environmental innovations (Beise and Rennings 2005; Jaffe et al. 2005; Rennings 2000).

¹ We treat the terms eco-innovation and environmental innovation as synonyms in this paper, as do many other researchers in the field (Hojnik and Ruzzier 2016). However, we do acknowledge that the two terms evolved from different academic fields and might therefore be used differently in the literature (Ekins 2010; Franceschini et al. 2016). For instance, the term environmental innovation is frequently used to describe environmental policy induced technological innovations, following the innovation inducement hypothesis. The term eco-innovation, on the other hand, is usually used more explicitly to describe innovations that contribute to positive environmental effects.

The second distinctive feature of environmental innovation is a natural consequence of the double-externality problem. Environmental innovations require regulatory support to be successfully developed and compete in the market. From an innovation economics perspective, technology push and demand pull mechanisms provide an explanation for the emergence and diffusion of ordinary innovations, but an additional triggering force, a regulatory push/pull, is required to stimulate environmental innovations (Rennings 2000). Regulations tend not only to encourage innovation, but can even help offset the costs of innovation development and lead to increased profits for the innovator. Environmental regulation can thus deliver a win-win situation for competitiveness and for the environment through its knock-on effect on environmental innovation. This phenomenon is commonly referred to as the Porter hypothesis and is yet another feature of environmental innovation (Porter and van der Linde 1995; Rexhäuser and Rammer 2014).

Alongside these peculiarities, empirical research on environmental innovations and green technologies has uncovered a number of stylized facts that can be used to differentiate them from non-green innovations. One important insight is that green technologies differ from regular innovations in terms of complexity. Green technologies generally require a higher degree of R&D cooperation and external knowledge in the developmental phase (De Marchi 2012; Ghisetti et al. 2015; Orsatti et al. 2020b; Quatraro and Scandura 2019), they rely on more novel and complex knowledge inputs (Barbieri et al. 2020a) and they require higher levels of technical expertise and cognitive skills to be developed (Consoli et al. 2016).

However, environmental innovations and green technologies do not form a homogeneous group. Instead, they can be further subdivided on the basis of various characteristics such as technological domain or field of application, leading to both different modes of innovation and different modes of valuation and market formation (Binz and Truffer 2017). Green technologies also differ in scale, with some green technologies relating to large infrastructure systems and others relating to consumer goods (Wilson et al. 2020). These technology-specific characteristics of course translate into differences in the innovation and diffusion process. Most of the peculiarities and stylized facts described above are, however, assumed to be common to all environmental innovations.

Based on these insights, numerous empirical studies have examined the determinants of environmental innovation in great detail (Hojnik and Ruzzier 2016; Horbach 2008, 2016, 2019; Horbach et al. 2013). Essentially, three different groups of determinants can be distinguished, most of which take effect on the level of the innovator and/or innovation adopter:

- Supply-side determinants (e.g. technological capabilities, competitive advantages)
- Demand-side determinants (e.g. expected market demand, environmental awareness)
- Institutional and political determinants (e.g. environmental policies and regulations)

This classification of the determinants of environmental innovations is well established in the literature and widely used in empirical studies. However, it largely ignores region-specific factors. Apart from the institutional and political determi-

nants, where some have an implicit geographical nature due to being linked to jurisdictions, the importance of geography and regional factors has received relatively little attention in empirical research on environmental innovation (Horbach 2014). This is surprising, given that the potential of environmental innovation and green industries for regional development has been discussed intensely for many years. In this context, it is generally assumed that green industries can have positive effects on regional economies and regional development (Capasso et al. 2019; Gibbs and O'Neill 2017). Countries and regions with strong green industries, exporting complex green goods, are, in fact, found to have increased capabilities to further innovate in green technologies while having lower CO₂ emissions (Mealy and Teytelboym 2020). Regions in which green industries thrive are also less affected by external economic shocks, meaning that green industries improve regional economic resilience (Vona et al. 2019). However, because green industries typically involve specialized jobs and rely on high levels of human capital, they present uneven growth opportunities for regions with varying factor endowments (Consoli et al. 2016; Sofroniou and Anderson 2021). Many of the peculiarities of green technologies, for example their complexity and their dependence on institutional support, also affect their geographical distribution, both in terms of innovation development and in terms of spatial diffusion. Given these impacts on regions, their economies and their environments, it is of significant value to better understand the *regional* determinants of environmental innovation, complementing existing knowledge on the general determinants listed above.

3 Critical review on regional determinants of environmental innovation

3.1 Review methodology and scope

In this section, we review the literature that deals with supply-side, demand-side and institutional conditions affecting environmental innovation that are determined or co-determined on the regional scale. While there are already useful systematic literature reviews that deal with the determinants of environmental innovations (Barbieri et al. 2016; Hojnik and Ruzzier 2016; Horbach 2019), we limit our review to those studies that help understanding why and how regions matter for environmental innovation. The review mainly draws on scholarly work from the regional studies community (see Table 1, especially research strand 1). However, we also include work from related disciplines that have an explicit implication for environmental innovation on the regional level. From a methodological perspective, our critical review of the literature on the regional determinants of environmental innovation follows a semi-systematic and integrative approach (Snyder 2019). The search process was initiated by conducting keyword searches in Web of Science and Scopus, building on a recently developed search string (see Hansmeier 2021 and Appendix). In addition, we performed citation searches on key articles identified during the initial search. Furthermore, we handpicked relevant publications based on expert knowledge. Inclusion criteria for the articles were that they had to have implications for research on environmental innovation in regional studies and regional science. All articles

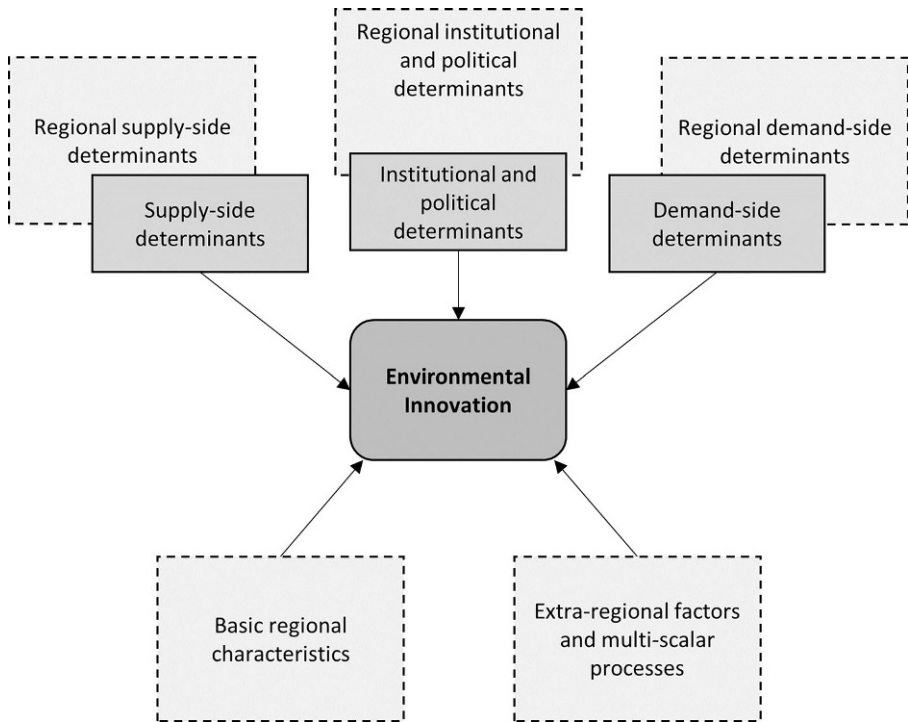


Fig. 1 Determinants of environmental innovation (own figure, based on Rennings 2000; Horbach 2008, 2019)

were reviewed and analyzed in detail, with a particular focus on the determinants of environmental innovation that have an explicit geographic dimension.

As mentioned before, three different groups of factors have been examined in detail in the eco-innovation literature: supply-side determinants, demand-side determinants, and institutional and policy determinants (Horbach 2008). While most of these determinants, particularly the pull factors that relate to expected market demand, take effect on the firm or innovator level (Horbach 2019), many determinants such as environmental regulations or technological capabilities and R&D activities on the supply side bear an explicit geographic dimension. For the critical review, we therefore use the established tripartite classification of the determinants of environmental innovations and reflect on them from a regional angle. We use this classification in particular because of the intellectual origins of this literature in the non-spatial analysis of environmental innovations and thus refrain from using an established classification from the regional studies literature (e.g. Hansen and Coenen 2015). In Fig. 1, we present the three groups of determinants, adding the regional dimension to each of these factors. Of course, basic regional characteristics such as demographics, infrastructure, socioeconomic development or environmental and physical-geographical factors will also play a role for environmental innovation. Another important regional characteristic is the local banking and financial (sub)system. The spatial organization and geographical concentration of the banking and financial

Table 2 Regional determinants of environmental innovation*Regional supply-side determinants*

Green technologies are (on average) more complex than non-green technologies and therefore require additional (local) knowledge and research inputs

Universities and other research facilities play a particularly important role for green technology development due to local knowledge spillovers, local human capital supply and university researchers involved in collaborative R&D processes

Green technologies generally benefit from additional external knowledge and open innovation modes, which emphasizes the relevance of efficient green regional innovation systems

Regions and countries are more likely to diversify into green technologies if local technological capabilities are related, even if a region is specialized in related dirty technologies

Relatedness to the local technological capabilities will also increase the probability that a region specializes in green technologies

A local knowledge base that is diversified over unrelated technologies (unrelated variety), will be more important for the development of green technologies that are in the early stage of the life cycle, while mature green technologies benefit from related variety

Regional demand-side determinants

The demand for environmental innovation triggers the emergence of green industries in a given region (local demand-pull)

The agglomeration of pioneering firms that use environmental innovations will increase the likelihood that other firms in the region will also adopt green technologies

Similar demonstration effects occur on the level of individuals and households, with geographic proximity to early adopters increasing diffusion rates

Regional environmental awareness and green political orientation induce the development and diffusion of green technologies

Regional institutional and political determinants

Environmental regulations and policies trigger market demand for green technologies that local firms and other innovators are likely to respond to, increasing regional green technology development

Environmental regulations and policies in a given region or country force the adoption of cleaner technologies, counteracting the double-externality problem associated with the diffusion of environmental innovations

Based on innovative and stringent environmental policies, regions and countries might become lead markets that demonstrate the benefits of an environmental innovation

Regulations and policies in other regions might trigger green technology development in the focal region

Place-based innovation policies that combine supply-side and demand-side rationales can trigger regional environmental innovation

The diffusion of environmental innovations also depends on informal institutions such as technology legitimization, which can differ profoundly between regions

The results presented in this table are largely based on quantitative studies using established innovation indicators such as patent data. Many of these studies treat green technologies and environmental innovations as a homogeneous group of technologies. However, doing so fails to acknowledge the heterogeneity and specificity of many environmental innovations. While the results are certainly valid for the majority of green technologies, they should not be interpreted as universally applicable. Given that we predominantly review quantitative studies, we provide only limited information on factors that are difficult to measure (e.g. informal institutions).

system differs greatly between countries, with some countries having a very centralized financial system and others having a more decentralized financial system (Klagge and Martin 2005). In any case, both the development and the diffusion of environmental innovations will depend on the systemic conditions offered by the regional financial and banking subsystem, e.g. driven by local availability of green venture capital (Demirel et al. 2019). In addition, extra-regional factors and multi-scalar processes are crucial for understanding how environmental innovations emerge and diffuse in regions (see among others Binz and Truffer 2017; Castellani et al. 2022; Njøs et al. 2020), which is why we have included these factors in the figure even though we do not consider them in the paper. Figure 1, in that sense, visualizes the underlying conceptual framework of this article and the structure of Sect. 3. Table 2 provides an overview of the most important insights on the determinants of the geography of environmental innovation that have received much attention in the literature so far. It is important to note that some of the findings presented in this Section relate to more than one group of determinants. For instance, regional environmental awareness can be considered as a demand side determinant while also being a region-specific informal institution. Another example are regional deployment policies that trigger demand for green technologies. This exemplifies that many factors as well as the groups of determinants are interdependent.

3.2 Regional supply-side determinants

On the supply side, determinants of environmental innovation mainly involve the technological capabilities of the innovator, including input factors such as R&D and (external) knowledge (Hojnik and Ruzzier 2016; Horbach 2008, 2019). These input factors for (environmental) innovations, however, depend not only on the innovating organization itself, but particularly on external knowledge, research collaborations and local knowledge spillovers, which the literature on the geography of innovations and regional innovation systems (RIS) has been demonstrating for more than two decades (Asheim et al. 2016). Regional innovation systems refer to the networks, institutions, and organizations that promote innovation and knowledge exchange in a specific geographic area. They are characterized by the close interactions between actors, such as universities, research institutions, firms, and public agencies, which create an environment conducive to innovation. RISs play an important role in promoting economic development by facilitating the creation, diffusion, and application of new knowledge and technologies within a particular region (Cooke et al. 1997; Tödtling et al. 2022). However, given their higher complexity (Barbieri et al. 2020a), green technologies will need additional (local) knowledge and research inputs when compared to regular innovations. A number of studies have analyzed these additional efforts needed for the development of environmental innovations, many of which include explicitly geographical features. For instance, Horbach (2014) finds that environmental innovations benefit more from spatial proximity to universities and research institutions than regular innovations. In addition, green technologies are more likely to emerge when academic inventors are involved in their development (Quatraro and Scandura 2019) while they also require higher human capital inputs (Horbach 2014). These empirical findings emphasize the importance of universi-

ties in ‘green regional innovation systems’ (Cooke 2010; Radinger-Peer and Pflitsch 2017), marking them as crucial actors in analyses of (the geography of) environmental innovations. The findings also highlight the complexity of green technologies, as they depend on more knowledge inputs that might be sourced from local partners or universities. Other supply-side regional determinants of green technology development include, *inter alia*, local knowledge stocks, agglomeration economies, and public research subsidies (Arranz et al. 2019; Corsatea 2016; Giudici et al. 2019). In that regard, it is noteworthy that green technologies are more likely to be invented in regions that are generally characterized by high technological capacity (Corradini 2019). Moreover, green technologies often stem from teams of inventors who are able to creatively recombine existing knowledge (Orsatti et al. 2020b). They also generally require a higher degree of R&D cooperation and external knowledge in the developmental phase (Cainelli et al. 2015b; De Marchi 2012; De Marchi et al. 2022b; Ghisetti et al. 2015; Horbach et al. 2013). Collaborative R&D processes will be particularly beneficial to environmental innovation emergence if partners are located in close geographic proximity (Ardito et al. 2019; Cainelli et al. 2012; Chiarvesio et al. 2015). The majority of the studies reviewed so far focus on the innovator and how the regional context as well as regional knowledge spillovers can lead to the development of green technologies. The findings carry important implications. That is to say, efficient innovation systems and open innovation modes will be crucial for successful eco-innovation efforts, with regions being a promising scale for innovation emergence. In other words, efficient green regional innovation systems are conducive to the development of green technologies because they facilitate the creation, diffusion, and application of new knowledge and technologies within a particular region, with universities, research institutions, firms, and public agencies all playing important roles in developing these systems (Cooke 2010, 2011).

Additional insights can be gained from an evolutionary perspective on green technology development in regions, shifting the focus from eco-innovators to the regional level. Much of this literature builds on the relatedness approach, stating that regional knowledge development depends on the availability of related knowledge in the region (Balland 2016). For instance, regional diversification into green technologies will depend on the local existing competencies, with relatedness playing a major role (Perruchas et al. 2020). Against this background, relatedness is relevant for green diversification processes irrespective of the technological domain, with some green technologies emerging in regions specialized in fossil fuel technologies (Sant’Alha and Boschma 2021; van den Berge et al. 2020). In other words, regions have many opportunities to diversify into the development of green technologies drawing on their existing competencies. However, Barbieri et al. (2020b) find that the role of related knowledge bases for developing green technologies will also depend on the technology life cycle. They show that unrelated variety, *i.e.* a local knowledge base that is diversified over unrelated technologies, will be more important for the development of green technologies that are in the early stage of the life cycle. For inventing mature green technologies, on the other hand, related variety will be more important. Technological relatedness also affects regional specialization processes, with relatedness increasing the likelihood of a region specializing in green technolo-

gies. In that sense, the local availability of key enabling technologies and digital skills is found to moderate the effect of relatedness on green regional specialization (Montresor and Quatraro 2020; Santoalha et al. 2021). While the literature reviewed in this section offers many important insights into green technologies and their regional drivers, many of the findings certainly do not apply to every green technology in the same way. More specifically, in many empirical studies, green technologies are treated as a homogeneous group, thereby failing to consider technology-specific characteristics.

3.3 Regional demand-side determinants

While demand-side determinants of environmental innovations have traditionally been associated with characteristics of the innovator or adopter, i.e. anticipating future market demand, high levels of environmental consciousness and environmental awareness (Horbach 2008), demand-side factors can also take effect on the regional level. The demand for environmental innovation can, in fact, trigger the emergence of green industries in a given region, highlighting the importance of local demand-pull mechanisms (Bednarz and Broekel 2020). Moreover, it is found that environmental awareness differs between regions or countries and positively affects the development of environmental innovations and the creation of green start-ups, which is a unique feature of environmental innovations when compared to non-green innovations (Corsatea 2016; Giudici et al. 2019; Horbach 2016). Regional demand can thus induce the development of environmental innovations. However, regional demand-side determinants might play a more important role in the diffusion phase. Many environmental innovations are very specifically tied to local environmental conditions and/or environmental problems and therefore tend to have strong regionalized demand and market formation processes (Binz and Truffer 2017). This does not apply to products in mass markets such as electric vehicles, but ranges from renewable energies (e.g. dependence on wind, sun, water) to climate change adaptation technologies (e.g. flood protection or water scarcity technologies). However, most quantitative studies on green technologies neglect these technology-specific features.

In addition, innovation diffusion is a social process in which early adopters can influence further potential adopters to use an innovation (Rogers 1962). This process unfolds through various channels of information exchange, being both simpler and more likely in geographical proximity (Hägerstrand 1967). While these diffusion mechanisms apply to all types of innovations, it is very likely that they are more important for environmental ones. Given the assumption that many potential adopters, particularly firms, often fail to anticipate the benefits of environmental innovations due to incomplete information as well as organizational and coordination problems, it is reasonable to conclude that demonstration effects from peers are particularly important for the diffusion of environmental innovations (Montalvo and Kemp 2008; Porter and van der Linde 1995). In fact, several lines of evidence suggest that the agglomeration of pioneering firms that use environmental innovations will increase the likelihood that other firms in the region will adopt environmentally benign technologies as well (Antonioli et al. 2016; Cainelli et al. 2012; Horbach and Rammer

2018), emphasizing the importance of local demonstration effects for environmental innovations. Of course, demonstration effects are not limited to innovation diffusion in firms, they also occur on the level of individuals or households, for instance in the case of PV installations (Graziano and Gillingham 2015; Wolske et al. 2020). Given that technological complexity hinders innovation diffusion in space (Balland and Rigby 2017), it is reasonable to assume that many green technologies characterized by high complexity will diffuse more slowly compared to non-green technologies. However, evidence on this relationship is scarce (Losacker et al. 2023).

3.4 Regional institutional and political determinants

It has long been recognized that regulations and policies are key to environmental innovation (Dupuy 1997; Jaffe et al. 2005; Rennings 2000). Internalizing external costs associated with the adoption of environmental innovations by means of adequate policies and regulations implies that administrative areas such as cities, provinces or nations with stringent environmental policies have higher diffusion rates of environmental innovations than areas with rather lax policies (Cainelli et al. 2015a; Frey 2012; Popp 2010; Woerter et al. 2017). Essentially, the same inducement effect applies to the diffusion of environmental innovations as to their development. While from a theoretical viewpoint, regulations ought to counteract the double-externality problem in the diffusion phase (Jaffe et al. 2005; Rennings 2000), they also induce the invention of green technologies, and not merely their use. More stringent environmental policies will lead to an increase in green technology development in a given region or country, with different types of policy instruments being effective for different green technology domains (Dechezleprêtre and Sato 2017; Johnstone et al. 2010, 2012). The immediate consequence of this causal relationship is an uneven distribution of green innovation output (and use) across space. Stringent policies that promote innovation development and diffusion in a region or country can, moreover, result in a so-called regulatory advantage that favors the creation of a lead market for environmental innovation, eventually driving global diffusion processes (Beise and Rennings 2005; Losacker and Liefner 2020). However, from a geographical perspective, the role of regulation and policies is much more complex. It is possible, for instance, that foreign environmental policies induce domestic green technology development and vice versa (Dechezleprêtre and Glachant 2013; Herman and Xiang 2019; Popp 2006). In particular, policies on the national or supranational level can foster the diffusion of environmentally benign technologies, for instance via carbon pricing (Baranzini et al. 2017). In fact, most studies on the effect of environmental regulation and policy on the development and diffusion of environmental innovations are at the level of nation states. The importance of regulation at the subnational level is less frequently studied, but might show similar inducement effects (Cao et al. 2019; Corsatea 2016; Losacker and Liefner 2020). One reason for the poor scholarly engagement with the innovation inducement effects of regional environmental regulations is the limited data availability on regional policies and policy stringency, with some authors using proxies such as political support to environmental protection or the regional exposure to regulations (Castellani et al. 2022; Losacker 2022; Santoalha and Boschma 2021). However, most countries simply de-

sign environmental policies on the national (or supra-national) level, with exceptions for a few countries and specific local environmental concerns (e.g. waste regulations in China, see Losacker and Liefner 2020).

On the regional level, place-based innovation policies are important to support green industries and to leverage the application of sustainable technologies. In that sense, it is important to support both green technology development, i.e. the supply side, and diffusion processes, i.e. the demand side, depending on the regional context and place specificities (Hansmeier and Losacker 2021; Tödtling et al. 2021). In fact, regional administrative bodies exhibit great potential to support diffusion processes using green public procurements, also nurturing early market formation and early adoptions (Ghisetti 2017; Lauer and Liefner 2019; Nesterova et al. 2020). Green public procurement, however, also exhibits positive effects on future green technology development within a region (Orsatti et al. 2020a).

While most of the studies mentioned so far focus on formal institutions such as regulations and policies, mainly driven by the double-externality problem associated with environmental innovation, less is known about the role of region-specific informal institutions (cultural-cognitive and normative institutions). In that regard, scholarly work in transition studies and regional path development provides useful insights. For instance, the diffusion of environmental innovations depends very much on legitimization or, in other words, on the willingness of consumers to adopt an environmentally benign technology (Bergek and Mignon 2017; Hekkert et al. 2007). As technology legitimization results particularly from place-specific factors such as localized informal institutions, legitimacy will differ between regions, leading to differences in diffusion rates across space (Heiberg et al. 2020; Rohe and Chlebna 2021). Moreover, regional legitimacy for a particular green technology is likely to depend on informal institutions and legitimacy of other technologies and industries in the region, underlining the local nature of cognitive and normative institutional support for environmental innovation (Jolly and Hansen 2022; Punt et al. 2022).

4 Suggestions for future research

As outlined in Sect. 3, several traditional determinants of environmental innovation bear an explicit regional imprint and scholars in regional studies have studied these factors assiduously. However, there are many open challenges that we have not been able to tackle. In this section, we propose three avenues for further research on the geography of environmental innovation, aiming at understanding the drivers of green technology development and diffusion in regions:

- Accounting for technology-specific dynamics and critically reflecting on the predominant binary distinction between green and non-green technologies.
- Exploring novel empirical opportunities to study both formal institutions, such as environmental regulation, and informal institutions, such as the legitimacy of technologies at the regional level.

- Shifting the focus of regional research on green technologies from innovation development towards the demand side and thus the diffusion of environmental innovations.

Again, the agenda mainly addresses the first research strand as depicted in Table 1. In order to inform and motivate the agenda, we will refer to other research strands on environmental innovation in regional studies, i.e. the geography of transitions and the green regional path development literature. On a personal note, we feel that there is limited interaction between these different research communities despite apparent shared concern about environmentally friendly regional development. We believe that this lack of scholarly exchange is due in part to differences in the preferred methodological approaches where the first strand of research predominantly relies on quantitative methods and econometric models, while the other two tend to work in a more case study-based manner using qualitative research designs. An implicit goal of this agenda is to bridge the divide between these communities. We believe that it will be very promising for the first research strand to integrate the conceptual and theoretical advances of the literature on green path development and transition studies into their quantitative research designs, which will also help the latter two fields to ‘reach for generic insights between cases’ (Köhler et al. 2019, p. 18). One crucial issue in this regard is the empirical operationalization of green technologies, where many quantitative studies fail to acknowledge insights from transition studies.

4.1 Towards technology-sensitive research

Most of the research papers that we have reviewed in Sect. 3 treat green technologies as a homogenous technology group, ignoring technology-specific dynamics. This is striking given the extant literature in transition studies that highlights how the importance of geographical scales for innovation and market formation processes differs between technological domains (Binz and Truffer 2017). As such, it is unclear to what extent the regional determinants of green technology development and diffusion described in Sect. 3 might vary across different technological domains. This is not only true for differences between technologies with local markets (e.g. wind power) and global markets (e.g. electric vehicles), but also for differences between granular (e.g. solar PV) and large-scale (e.g. CCS) technologies (Huenteler et al. 2016; Wilson et al. 2020). While all these technologies are considered ‘green’, they have distinct (spatial) characteristics in terms of technology development and, more importantly, in terms of diffusion. For instance, green technologies in the energy or transportation sectors face additional diffusion barriers due to sunk costs of existing physical infrastructure and local assets that strengthen unsustainable regimes (Negro et al. 2012; Unruh 2000). For example, transportation, supply infrastructures and waste infrastructures correspond to and perpetuate existing patterns of urban land use and the use of established types of buildings, and are thus extremely difficult to change. Moreover, in the energy sector, markets are often shaped by natural monopolies, i.e. access to infrastructure. These monopolistic bottlenecks hinder the market entry of new innovating firms, limiting sustainable action to dominant incumbents (Walz 2007). These barriers directly translate into regional path-dependen-

dencies, making it more difficult for some regions to develop and diffuse certain types of green technologies (Martin and Sunley 2006; Truffer et al. 2015). Another promising but so far under-researched technological field in this regard are circular-economy innovations, which are likely to show a distinct regional pattern (Antonoli et al. 2022). More generally, it is questionable to what extent some of the ‘stylized facts’ on environmental innovation described in Sects. 2 and 3 might be invalid for certain green technologies. For instance, while green technologies are found to be, on average, more complex than non-green technologies (e.g. Barbieri et al. 2020a) and to depend on high levels of (regional) knowledge inputs (Cainelli et al. 2015b; Horbach 2014), additional research is required that digs deeper into variation of these stylized facts between technological domains. This will help to understand the regional determinants of green technology development in more detail, considering both place-specificities and technology-specificities. Future research on green technologies in regional studies should thus go beyond the use of green technology domains as simple ‘control’ variables and engage more meaningfully with technological characteristics.

4.2 Solving empirical challenges on regional institutional factors

In Sect. 3.4, we have pointed to the fact that institutional factors, both formal institutions such as regulations and informal institutions such as societal norms or beliefs, will contribute to how successful a region can develop and diffuse green technologies. Yet, several challenges remain in empirically measuring institutions, making it difficult to assess their importance against other factors. For formal institutions, it is evident that regulations and environmental policy play a decisive role in the development and diffusion of environmental innovations. However, most empirical studies examine this relationship at the (inter)national level rather than at the (inter)regional level. Since regions face different environmental pressures and demands, regional differences in regulation and environmental policy do exist in some cases, e.g. in waste management or air pollution. We feel that there is much room for further research on regional regulations, particularly for countries with strong regional governments (China, Germany, USA, etc.) where differences in environmental policy stringency between regions are pronounced. However, in most cases, environmental policy is implemented at the national (and sometimes supra-national) level. Still, this does not mean that regions are homogeneously affected by these environmental policies. In fact, environmental regulations will affect regions differently, for example depending on the local industrial structure. Environmental regulations at the national level therefore have varying regional impacts, which at the same time translate into different regional incentives for green technology development and use. Empirical studies therefore can choose to not directly monitor regional environmental policy, but rather the regional exposure to environmental policy. Some empirical studies already use this approach to measure regional effects of regulations (Castellani et al. 2022; Losacker 2022), yet the same problem arises that we discussed in Sect. 4.1. That is to say, empirical studies fail to acknowledge technological and sectoral specificities within the green technology sphere. For instance, studying the effect of the regional exposure to one pollutant (e.g. NO_x) on regional

green technologies, does not do justice to the scope of green technologies that exist (e.g. from water treatment technologies to climate change mitigation). To counteract this problem, we propose two possible approaches. Either studies need to be more technology specific and stop treating green technologies as a homogeneous group (see Sect. 4.1), or studies need to take into account the multi-dimensionality of environmental policy. The latter means that regional indicators of environmental policy must also take into account the variety of environmental regulations, and not just encompass one pollutant or one environmental problem. This also raises the need for research approaches employing multi-level designs that take into account both regional and national policy factors. In this context, there is also a need for further research on the synergies or conflicts between environmental policy and innovation policy (van den Bergh et al. 2011), and the multi-level governance thereof.

Given the significance that eco-innovation researchers attach to the role of formal institutions such as environmental policy and regulation, they often neglect the role of informal institutions (cultural-cognitive and normative). While informal institutions, predominantly the regional legitimization of green technologies, are already being studied in the geography of transitions and regional path development literature, quantitative evidence on their impact on green technologies is still lacking (Jolly and Hansen 2022; Rohe and Chlebna 2021). We believe that research on the regional determinants of environmental innovation has much to learn from the aforementioned literature on the legitimacy of green technologies and at the same time can contribute to improving the empirical evidence on that relationship. We also feel that eco-innovation researchers do not per se underestimate the importance of informal institutions, but merely fail to operationalize and measure them empirically at the regional level. While some initial attempts have been made in regional studies (Punt et al. 2022), we argue that the potential of studying regional informal institutions remains unexploited. There are various sophisticated methods for measuring legitimacy and norms based on textual data, and research on this topic is evolving rapidly, as are the machine learning and natural language processing techniques used (e.g. Dehler-Holland et al. 2022; Weiss and Nemeček 2021). However, these studies have so far been blind to spatial issues. We therefore argue that the combination of modern techniques for measuring informal institutions and innovative regionalized textual data sources (e.g. Ozgun and Broekel 2022) have huge potential for mapping the regional legitimacy for a given green technology. In summary, we suggest that researchers working on regional determinants of environmental innovation need to interact more closely with other fields, both in terms of theoretical concepts and in terms of methodological advances in order to unveil the effects of institutions.

4.3 Towards a demand-side turn in regional research on green technologies

One of the most important issues in the geography of environmental innovation literature, in our view, relates to technology adoption and diffusion. Traditional research on the geography of innovation has for many years focused on the regional hotspots of innovation development. As a result, researchers were able to gain a broad understanding of the regional (supply-side) factors that contribute to the emergence of innovations (Asheim et al. 2016). However, this perspective is not sufficient for the

analysis of environmental innovations, since environmental innovations only unleash their positive effects on the environment when they are widely diffused. Put simply, society will not solve ecological and climate crises by inventing green technologies, but they must be adopted on a large scale. This implies that we not only need to understand which regional factors contribute to the emergence of innovations, but we need to comprehend, in particular, which regional factors on the demand side facilitate the market success and adoption of environmental innovations (see also Gibbs 2006). Research on the geography of environmental innovation should thus refrain from focusing too much on the supply-side factors for the development of green technologies. In contrast, more attention should be paid to regional factors relating to the diffusion of green technologies. The demand side is already receiving increasing attention in the two related research strands on environmental innovations in regional studies (see Table 1). In the literature on green path development, it is generally assumed that the regional industry structure poses significant opportunities and challenges for different types of regions (Grillitsch and Hansen 2019). Yet, little research has been conducted on how the regional industry structure relates to the use and diffusion of green technologies. Research should not only focus on how regions can build green industries to drive employment and regional development. Instead, future research should focus on how the existing (or new) local industries can use green technologies to establish more environmentally friendly production processes.

Furthermore, research in transition studies has already identified many factors that influence the use and diffusion of green technologies from a socio-technical perspective (Hansen and Coenen 2015). However, many of these factors have not been sufficiently studied in empirical research, and we believe that there needs to be a general turn in research on environmental innovation. This demand-side turn in geographical research on green technologies will have far-reaching consequences for the way research is designed. First and foremost, the research focus will shift to regions that are typically ignored in the literature, such as rural areas that do not contribute to the development of innovations. However, these regions are in a significant position to use environmental innovations, e.g. in energy, agro-food or in transportation sectors, and to provide feedback effects on the further development of green technologies. Secondly, researchers will need to develop methodological approaches that capture the use of green technologies rather than their development in order to successfully unveil the regional dimension of innovation diffusion (e.g. Losacker 2022).

5 Conclusion

This article set out to achieve two research objectives, which were (1) a critical literature review of the regional determinants of environmental innovations and (2) the development of an agenda for future research in regional studies on the geography of environmental innovations.

(1) After conducting a critical analysis of the relevant literature, we have identified the significance of regional factors in driving the development and diffusion

of green technologies. Our findings highlight the positive influence of regional determinants, such as regional R&D collaborations, university-industry collaborations and technological relatedness. Furthermore, regional environmental awareness and demonstration effects have been found to play a crucial role in the emergence and diffusion of environmental innovations. Although evidence at the regional level is somewhat limited, we find that environmental regulations also contribute to eco-innovation activities. (2) The insights gained from our literature review have paved the way for future research endeavors, suggesting three avenues for further investigation. Firstly, we propose moving away from a simplistic green vs. non-green categorization and conducting more nuanced studies that take into account specific technological contexts. Secondly, we advocate for a comprehensive and critical exploration of regional institutions, encompassing both formal and informal institutions. By doing so, we can deepen our understanding of their influence on environmental innovation. Lastly, we propose a demand-side turn in research on the regional determinants of environmental innovation to understand the diffusion of green technologies across space. Shifting the research focus to less innovative regions could lead to greater use of environmental innovations and ultimately, positive environmental effects.

Given the synthesis of the rich literature in the field of the geography of environmental innovation, our review and agenda for future research have important implications for (regional) policy, particularly in the fields of innovation and environmental policy. While it is widely acknowledged that a well-designed policy mix combining supply-side and demand-side instruments is necessary to support green technology efforts, there has been less critical scrutiny of the spatial reach and multi-level governance of such an approach (Hansmeier and Losacker 2021; Tödtling et al. 2021; van den Bergh et al. 2011). Innovation policy tends to be region-specific, while environmental policy is typically established at the national level, leading to governance challenges in harmonizing the two. Regional governments should thus design innovation policies in a place-based fashion and pay attention to their interplay with regional or national environmental policies, which are often sector-specific or technology-specific. Our review also highlights the potential of regional public procurement to promote the development and diffusion of environmental innovations and contribute to environmentally friendly regional development. However, regional resource endowments may result in increasing interregional divergence, with environmental innovations emerging and diffusing only in prosperous regions, thereby reinforcing socio-economic disparities. Policymakers face the challenge of making the green transition as inclusive as possible. Overall, our findings suggest that policymakers need to adopt a more nuanced and comprehensive approach to eco-innovation policy, one that considers the spatial and multi-level governance challenges and promotes inclusive regional development.

Last but not least, there is at least one more crucial issue that we need to mention in this article. That is to say, while the focus of this paper explicitly lies on regional factors for the development and diffusion of environmental innovations, we would like to emphasize the value of a global and multi-scalar perspective that we have largely ignored in this paper, as global and extra-regional processes, both in innovation development and in market formations, are essential for many green technologies. This relationship has not only been investigated in transition studies

(Binz et al. 2014; Binz and Truffer 2017) and in the regional path development literature (Njøs et al. 2020; Trippel et al. 2018) but is increasingly recognized in the literature on (regional) determinants of green technologies as well (Castellani et al. 2022; De Marchi et al. 2022a). On a personal note, this theme might be a good starting point for more scholarly exchange between the different research streams in the future, which we would like to encourage.

6 Appendix

The semi-systematic and integrative approach to the literature review that we adopt in this paper builds on methodological considerations discussed by Snyder (2019). The search strings we used for the initial scoping of the relevant literature were developed by Hansmeier (2021).

Search string in Scopus 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”))

Search string in Web of Science 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)

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